DOCTOR OF PHILOSOPHY

Aqueous carbon losses from the Glenfeshie Mòine Mhór

Bryder, Emma Louise

Award date:
2020

Aqueous carbon losses from the Glenfeshie Mòine Mhór

Emma Louise Bryder,

BSc (Hons), MSc

Geography

School of Social Sciences

University of Dundee

Submitted in fulfilment of the Degree of Doctor of Philosophy

April 2020

Contents

List of tables vi
List of figures viii
List of acronyms and abbreviations xi
Terminology xii
Acknowledgements xiv
Declaration xvi
Abstract xvii
1. Introduction 1
 1.1 Project rationale 1
  1.1.1 Global importance of peatlands 1
  1.1.2 Peatlands and deer management in Scotland 2
  1.1.3 Designated land in Scotland 3
  1.1.4 Peatland policy and funding sources 4
 1.2 Justification of study 5
 1.3 Aims and objectives 6
 1.4 Thesis outline 6
2. Literature review 8
 2.1 Peatland classification 8
 2.2 Peatland formation 12
  2.2.1 Peatland timeline 12
  2.2.2 Controls on peat formation 14
  2.2.3 Peatland structure 18
  2.2.4 Peatland growth 19
 2.3 Peatland hydrology 20
  2.3.1 Controls and drivers of peatland hydrological change 20
  2.3.2 Water supply in peatlands 21
  2.3.3 Peatland microhabitat 22
  2.3.4 Regulating rainwater runoff 23
  2.3.5 Challenges in gathering upland hydrological data 27
 2.4 Peatland ecology 28
  2.4.1 Peatland vegetation 29
 2.5 Interactions between peatland hydrology and ecology 31
  2.5.1 *Sphagnum* and water table 31
  2.5.2 Freeze-thaw cycle in peatlands 31
  2.5.3 Hydroperiod regime 32
  2.5.4 Peatland palaeohydrology 32

2.5.5 Micro-relief features within peatlands 33
2.5.6 Zonation within peat bogs 34
2.5.7 Morphological classification 35
2.5.8 Ecological management of peatlands 36
2.6 Peatland function 37
2.6.1 Biogeochemical cycle 37
2.6.2 Biological activity 37
2.6.3 Carbon cycle 39
2.6.4 Carbon storage 40
2.6.5 Carbon fluxes and hydrology 42
2.6.6 Fluvial carbon export 42
2.6.7 Previous studies and trends in aquatic carbon 47
2.7 Peat erosion 48
2.7.1 Degradation of peatlands 48
2.7.2 Drivers of erosion 50
2.7.3 Anthropogenic influence on peat erosion 52
2.8 Management of upland peat 55
2.8.1 Understanding linkages 55
2.8.2 Land management 56
2.9 Red deer (*Cervus elaphus*) 59
2.9.1 Size of deer 59
2.9.2 Territory and ranging patterns of deer 61
2.9.3 Management of deer populations 63
2.10 Peatland restoration 66
2.10.1 Techniques for restoration 66
2.10.2 Regeneration of peatlands 68
2.10.3 Peatland water balance 68
2.10.4 Benefits of peatland restoration 69
2.11 Literature review summary 70
3. Site characterisation 71
3.1 History 71
3.1.1 Place names 71
3.1.2 Land use 72
3.1.3 Ownership of Glenfeshie estate 73
3.2 Mòine Mhór topography 74
3.2.1 Mòine Mhór soils 75
3.2.2 Classification of the Mòine Mhór peatland 77
3.2.3 Condition of the Mòine Mhór 77
3.3 Mòine Mhór geology 79

3.4 Cairngorm AWS 81
3.5 Allt a' Mharcaidh ECN AWS 84
3.6 Conservation 85
3.7 Flora on the Mòine Mhór 87
3.7.1 Composition 88
3.8 Fauna within the Mòine Mhór 92
3.8.1 Red deer – *Cervus elaphus* 93
3.8.2 Reindeer - *Rangifer tarandus* 97
3.8.3 Mountain hare - *Lepus timidus* 99
3.8.4 Upland birds 101
3.8.5 Fox – *Vulpes vulpes* 103
3.9 Summary 103
4. Materials and methods 105
4.1 Overview 105
4.2 Equipment and software 107
4.3 Water level and temperature 108
4.3.1 HOBO® logger location 108
4.3.2 HOBO® logger set-up 109
4.3.3 HOBO® logger deployment 109
4.3.4 Barometric logger 110
4.3.5 Converting pressure to level 110
4.4 Interpolation of missing Mòine Mhór barometer data 111
4.4.1 Analysis and comparison of results using different methods 114
4.5 Flow gauging 120
4.5.1 Creation of flow rating curves 123
4.6 IHACRES rainfall-runoff modelling 126
4.7 Water sampling 129
4.7.1 Automatic water sampling 130
4.8 Statistical analysis 131
4.9 Precipitation data 132
4.10 Cairngorm ECN AWS precipitation data 136
4.11 Continuous water chemistry monitoring 137
4.11.1 Spectro::lyser location 137
4.11.2 Spectro::lyser set-up 137
4.11.3 Spectro::lyser deployment 138
4.11.4 Spectro::lyser operation and maintenance 140
4.12 Inorganic carbon monitoring 141
4.13 Erosion 144
4.14 Laboratory work 146

4.15 Health and safety 150
5. Results 152
5.1 Introduction 152
5.2 River Feshie level and flow rates 153
5.2.1 Location to study site 153
5.2.2 River level 154
5.2.3 Event hydrographs 155
5.2.4 Mean daily flow 157
5.2.5 Flow duration curve 160
5.2.6 Baseflow Index 162
5.2.7 River Feshie summary 162
5.3 Mòine Mhór stream levels and flow rates 163
5.3.1 Location 163
5.3.2 Stream levels 163
5.3.3 Stream temperatures 166
5.3.4 Flow rate in the Mòine Mhór streams 172
5.3.5 Daily flow data 181
5.3.6 Annual runoff on the Mòine Mhór 185
5.3.7 Hydrological comparison of catchments 188
5.4 IHACRES rainfall-runoff modelled flow 189
5.5 Precipitation across the Mòine Mhór 192
5.5.1 Precipitation summary 193
5.5.2 Precipitation throughout Glen Feshie 195
5.6 Chemical properties of the water sampled from the Mòine Mhór 203
5.6.1 Laboratory results from analysed water samples 204
5.6.2 Seasonal water chemistry 212
5.6.3 Water chemistry and daily flow data 216
5.6.4 Mòine Mhór streams summary 218
5.7 Spectro::lyser data 218
5.7.1 Continuous data 219
5.7.2 Spot sampling 224
5.8 High flow events 228
5.8.1 Autosampler 234
5.9 Inorganic carbon 243
5.9.1 Calculation of DIC carbon export 248
5.10 Erosion of stream banks 249
5.11 Aquatic carbon budget 256
5.11.1 DOC export from the study streams 256
5.11.2 DOC loss from the MM SE T 260

5.11.3 Erosion block study 262
5.12 Results summary 264
6. Discussion 265
6.1 Summary of findings 265
6.1.1 Condition of the peatland and streamflow 265
6.1.2 Seasonality 267
6.1.3 Variability in streamwater quality 269
6.1.4 Storm events 272
6.1.5 Aquatic carbon budget 273
6.2 Processes affecting aquatic carbon export 277
6.3 Restoration and wider implications 280
7. Conclusion 288
7.1 Data limitations and future research recommendations 289
7.2 Concluding remarks 293
8. References 295
9. Appendices 316
9.1 Appendix A: Feshie papers 317
9.2 Appendix B: Field work diary 323
9.3 Appendix C: Water level quality assurance 337
9.4 Appendix D: Risk assessment for field work 341
9.5 Appendix E: Multiple comparisons test 345
9.6 Appendix F: Water chemistry and daily flow 347
9.1 Appendix G: DOC export calculation 354

List of tables

Table 1-1: Benefits provided by peatlands if in a healthy state and pressures placed on peatlands 2
Table 2-1: Comparison between the main peatland types found in the UK 10
Table 2-2: Description of individual mire units (mesotopes) 36
Table 2-3 Categories and key features associated with peat condition/degradation 50
Table 2-4: Legislation relating to the protection of peatlands 58
Table 2-5: Development of red deer (*Cervus elaphus*) antlers 60
Table 2-6: Estimated population of deer species in Scotland 61
Table 2-7: Annual summary of benefits, damages and management costs associated with deer and deer management 65
Table 3-1: Place names (Gaelic to English translation) and their location on or around the study site 71
Table 3-2: Summary of the main characteristics of the study site 81
Table 3-3: Cairngorms Automatic Weather Station 83
Table 3-4: Details of wildlife cameras situated on the Mòine Mhór 95
Table 3-5: Field notebook observations of red deer on the Mòine Mhór 96
Table 4-1: Summary of study catchment characteristics 106
Table 4-2: Summary of the main variables measured and methods used 107
Table 4-3: Computer software packages and equipment used in this study 108
Table 4-4: Sampling locations of the monitored streams used in the study 109
Table 4-5: Stream temperature (°C) correlation matrix 112
Table 4-6: Regression Analysis of observed MM pressure against calculated, 2015 116
Table 4-7: Analysis of difference between observed MM pressure and calculated, 2015 117
Table 4-8: Gauging information for each monitored stream across the study site 121
Table 4-9: Number of water sampling occasions in the eight study streams 130
Table 4-10: Statistical scale for the p value significance rating 131
Table 4-11 Regression statistics analysis output 132
Table 4-12: Summary of precipitation data sources 135
Table 4-13: Cairngorms TBR data source 137
Table 4-14: Location and position of astro turf mats and buckets 145
Table 5-1: Annual runoff for the River Feshie 160
Table 5-2: Completeness of HOBO data loggers for the monitored streams..... 165
Table 5-3: Annual mean stream water temperature in the monitored catchments covering from 2013-2016 167
Table 5-4: Annual and seasonal mean stream water temperature in the monitored catchments covering from 2013-2016 168
Table 5-5: Justification for exclusion of gaugings from rating curves to improve fit 174
Table 5-6: Flow for the monitored streams across the years 180
Table 5-7: Annual runoff values for the monitored streams on the Mòine Mhór 186
Table 5-8: Comparisons of the hydrology of the study site catchments 188
Table 5-9: Hydrological summary for MM SE T modelled stream flow 191
Table 5-10: Amount of precipitation (mm) and precipitation days (>1 mm) from the UK climate network of observing stations 192
Table 5-11: Amount of precipitation (mm) recorded from the Glenfeshie hydro-meteorological monitoring network. 200

Table 5-12: Amount of precipitation (mm) recorded from the Cairngorm ECN AWS 201
Table 5-13: Summary statistics for each of the streams monitored 210
Table 5-14: 1-way ANOVA results for the variation between the monitored streams for measured water quality parameters 212
Table 5-15: Summary table for 2014, 2015 and 2016 spectro::lyser data 221
Table 5-16: Mean spectro::lyser values across the seasons 223
Table 5-17: Summary of events sampled 236
Table 5-18: Replicated peat block survey results for 2015 and 2016 250
Table 5-19: Summary of astro turf mats and bucket survey 252
Table 5-20: Mean predicted DOC concentrations for the monitored streams based on grab water samples 259
Table 5-21: Summary of the maximum and minimum DOC flux from the study streams 260
Table 5-22: DOC export from the MM SE T 261
Table 5-23: Calculation of the amount of loose material on the river banks of the Mòine Mhór in 2015 and 2016 262
Table 6-1: Summary of aquatic carbon budget for the Mòine Mhór south east tributary study stream 274
Table 6-2: Rates of carbon sequestration from peatland habitats 276

List of figures

Figure 2-1: Distribution and classification of peatland habitat across Scotland . 11
Figure 2-2: Raised bog (A) and blanket bog formation (B) 13
Figure 2-3: Peatland calendar for Britain 14
Figure 2-4: Annual mean precipitation and precipitation days 1981 - 2010 16
Figure 2-5: Peatland soil layers 18
Figure 2-6: Schematic diagram of Clymo's 1984 model of bog growth 20
Figure 2-7: Peatland microhabitat landscape in Estonia 23
Figure 2-8: Steady state runoff rates by vegetation type with rainfall intensity 25
Figure 2-9: Water pathways in an intact (a) and degraded peatland (b) 27
Figure 2-10: Common bog vegetation 29
Figure 2-11: The difference between a hummock and a hollow 34
Figure 2-12: Small scale variability in species occupying peatland habitat 35
Figure 2-13: Generalised responses of blanket mire vegetation to grazing, burning and drainage 37
Figure 2-14: Biogeochemical cycling of organic matter in the soil and water column 38
Figure 2-15: Surface exchange of carbon dioxide and methane in a peatland system.. 40
Figure 2-16: UK soil carbon map with carbon density in kg m^{-2} 41
Figure 2-17: Carbon uptake and release pathways for upland peat 43
Figure 2-18: The Dubringer moor 52
Figure 2-19: The roles of contributory factors to vegetation change and erosion in a sensitive blanket mire system.. 53
Figure 2-20: The main species of deer in Scotland with the male pictured above and the female pictured directly below 61
Figure 2-21: Flow diagram of how deer populations function 63
Figure 3-1: Glen Feshie as seen by others 73
Figure 3-2: Boundary of Glenfeshie estate as of 2015 covering 43,000 ha........ 74
Figure 3-3: Mòine Mhór study site slope angle 75
Figure 3-4: Predominant Soil Types.. 76
Figure 3-5: Classification of peatland habitat on the Mòine Mhór 77
Figure 3-6: Designated study site 78
Figure 3-7: Bare peat on the Mòine Mhór 79
Figure 3-8: Solid geology map showing Cairngorm granite (red) and Dalradian rock (yellow) 80
Figure 3-9: Cairngorm Automatic Weather Station data............................ 82
Figure 3-10: Cairngorm (Allt a' Mharcaidh) ECN AWS data 85
Figure 3-11: Natural regeneration in Glenfeshie 87
Figure 3-12: Eidart upland plateau vegetation....................................... 89
Figure 3-13: Garbhlach upland plateau vegetation.................................. 90
Figure 3-14: Flora on the Mòine Mhór 91
Figure 3-15: Flowering flora on the Mòine Mhór 92
Figure 3-16: Outlook of wildlife camera onto an area of bare peat at the Eidart catchment 95
Figure 3-17: Red deer on the Mòine Mhór 96
Figure 3-18: Hoof prints on the Mòine Mhór 97
Figure 3-19: Reindeer antlers on the Mòine Mhór 98
Figure 3-20: Mountain hare on the Mòine Mhór 100
Figure 3-21: Game birds on the Mòine Mhór..102
Figure 3-22: Red fox on the Mòine Mhór 103

Figure 4-1: Monitored streams on the Mòine Mhór plateau 119
Figure 4-2: The location of flow gauging at monitored streams across the study site..120
Figure 4-3: Manual stage reference for each of the monitored streams 122
Figure 4-4: Catchment areas of monitored streams on the Mòine Mhór plateau126
Figure 4-5: Parameters and empirically defined values following the IHACRES model fitting exercise 128
Figure 4-6: Water sampling fieldwork activities 131
Figure 4-7: Mòine Mhór storage gauge...133
Figure 4-8: Location of meteorological monitoring equipment in Glenfeshie ...134
Figure 4-9: Spectro::lyser graph 138
Figure 4-10: Measuring path and orientation of the Spectro::lyser in stream...139
Figure 4-11: Mòine Mhór SE tributary field instrumentation for the spectro::lyser 140
Figure 4-12: Method used to make Vaisala Carbocap sensor watertight 142
Figure 4-13: Vaisala Carbocap CO_2 readings, raw and corrected for pressure ..144
Figure 4-14: Picture of astro turf and buckets in position 146
Figure 4-15: Schematic diagram of a gas chromatograph 149
Figure 4-16: Relationship between fluvial carbon compounds.....................150
Figure 5-1: Catchment boundary for the Feshie at Feshie Bridge.................153
Figure 5-2: Feshie river level from 1st September 2013 to 4th November 2016..154
Figure 5-3: A snow covered upper Feshie catchment area reflective of winter conditions...155
Figure 5-4: Mean daily stream flow hydrographs for the River Feshie............156
Figure 5-5: Photographs of the wider Feshie catchment during river level peaks 157
Figure 5-6: Feshie Bridge daily flow hydrographs..................................160
Figure 5-7: Flow duration curves..161
Figure 5-8: Stream level and stream temperature for the monitored streams .164
Figure 5-9: Relationship between air temperature and stream temperature (Nov 2013 – Mar 2016)..170
Figure 5-10: Relationship between air temperature and stream temperature (Aug 2014 – Sept 2016)..171
Figure 5-11: Rating curves for the monitored streams on the Mòine Mhór 178
Figure 5-12: Mean gauged daily flow across the monitored streams 182
Figure 5-13: Snow covered stream...183
Figure 5-14: Mean gauged daily flow across the monitored stream inset........184
Figure 5-15: Modelled stream flow for the MM SE T...............................190
Figure 5-16: Precipitation amount for 2014 displayed as % of the 1981-2010 average 194
Figure 5-17: Allt a'Mharcaidh Automatic Weather Station (AWS) monthly precipitation totals..195
Figure 5-18: Precipitation data for Glenfeshie available during the study period 197
Figure 5-19: Combined accumulation precipitation data for Glenfeshie.........198
Figure 5-20: Precipitation data for the Cairngorm ECN AWS available during the study period 201
Figure 5-21: Relationship between precipitation and flow.........................202
Figure 5-22: Replicate samples for CD L 205
Figure 5-23: Box and whisker plots for various parameters tested for monitored streams...207
Figure 5-24: Column scatterplot of seasonal laboratory results for the monitored streams...215

Figure 5-25: Water chemistry and daily flow values for MM SE T 217
Figure 5-26: Photo of spectro::lyser before cleaning and the turbidity graph for that period 220
Figure 5-27: Spectro::lyser data graphed..222
Figure 5-28: Manual spectro::lyser measurements 225
Figure 5-29: Dissolved organic carbon (DOC) data comparison 227
Figure 5-30: River fords on the morning of Tuesday 12th August 2014...........229
Figure 5-31: Flow and water quality on the 12th August 2014 231
Figure 5-32: Filter paper photographs 233
Figure 5-33: Flow and water quality on the 27th August 2015 234
Figure 5-34: Autosampler and spectro::lyser results from MM SE T...............242
Figure 5-35: Mòine Mhór SE tributary dissolved CO_2 measurements from Vaisala Carbocap and headspace samples data 244
Figure 5-36: Time series of dissolved CO_2 stream temperature and flow rate in MM SE T in March-December 2015 245
Figure 5-37: Seasonal changes in dissolved CO_2 at MM SE T........................246
Figure 5-38: Astro turf mat as discovered on 4th August 2016 253
Figure 5-39: Bare peat cracking during the summer months on the Mòine Mhór254
Figure 5-40: Obstacles to flow within the headwater streams 255
Figure 5-41: Predicted DOC concentrations for 2014, 2015 and 2016 259
Figure 6-1: Snowmelt variability between May 2015 and May 2016...............269
Figure 6-2: Processes affecting aquatic carbon export on the Mòine Mhór 277
Figure 6-3: Picture taken on the 15th July 2015 within the MM SE T catchment, showing erosion down to the mineral strata with deer resting on the hillside above. 280
Figure 6-4: Peat hags three years post restoration at the North Pennines (The AONB Partnership, 2019). 281
Figure 6-5: Hag re-profiling on upland blanket peatland as demonstrated by Drumclog Plant Ltd. 283
Figure 6-6: Post ditch blocking works 284
Figure 6-7: Snowpack melting on the river banks of the CD L 285

List of acronyms and abbreviations

AOD	above ordnance datum
AWS	automatic weather station
BFI	baseflow index
BP	before present
CEH	Centre for Ecology and Hydrology
CH_4	methane
CO_2	carbon dioxide
CCP	climate change plan
DMG	Deer Management Groups
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
EC	European Commission
Ecohydrology	hydrology, ecology and biogeochemistry
ECN	Environmental Change Network
EPS	extracellular polymeric substances
Ericoids	small and tough leaves, resembling those of heather
EU	European Union
FDC	flow duration curve
ft.	foot/feet
FTU	Formazin Turbidity Units
GC	Gas chromatography
GIS	Geographic Information System
Gt	Gigatonne
GHG	greenhouse gas
HCO_3	bicarbonate
ha	hectare
HU	Hazen Units
km	kilometer
m	metre
mm	millimetre
NRFA	National River Flow Archive
NDIR	Non-Dispersive Infra-Red
NNR	National Nature Reserve
NO	Nitric Oxide
N_2O	Nitrous Oxide
PTFE	polytetrafluoroethylene
RDC	Red Deer Commission
SAAR	Standard Average Annual Rainfall
SAC	Special Area of Conservation
SEPA	Scottish Environment Protection Agency
SNH	Scottish Natural Heritage
SPA	Special Protection Area
SRDP	Scottish Rural Development Programme
SS	suspended sediment
SSSI	Site of Special Scientific Interest
The study site	The Mòine Mhór study area
TBR	tipping bucket rain gauge
TOC	total organic carbon
UV-Vis	Ultraviolet–visible spectroscopy
WFD	Water Framework Directive
^oC	degrees Celsius
%	percentage

Terminology

Ablation	refers to all processes that remove snow, ice, or water from a glacier or snowfield.
Aeolian	Caused by the wind
Aerobic	Occurring in the presence of oxygen
Acrotelm	Biologically active, affected by fluctuating water table, organic matter decomposes aerobically
Afforestation	Establishment of a forest or stand of trees in an area where there was no previous tree cover
Allochthonous	Originated at a distance from its present position
Anaerobic	Occurring in the absence of free oxygen
Autochthonous	Formed in its present position
Autotrophs	Organism able to manufacture nutrients from inorganic materials
Baseflow	Sustained flow of stream in the absence of any direct runoff
Blanket bog	Upland rain-fed peat accumulation
Boreal	Northern hemisphere, sub-arctic climate
Carbon sequestration	Natural or artificial removal of carbon dioxide or other forms of carbon into long-term storage in a solid or liquid form
Catotelm	Organic matter supplied from the acrotelm forms peat in waterlogged anaerobic conditions
Desiccation	State of extreme dryness
Diagenesis	The physical and chemical changes occurring during the conversion of sediment to sedimentary rock
Diffusion	Net movement of molecules from a region of high concertation to one of lower concertation continuing until the concentration of substances is uniform throughout
Diplotelmic	Peatland of two distinctive hydrological layers
Ecohydrology	Interactions between the water and ecosystems
EPS	Secreted by microorganisms – establish the functional and structural integrity of biofilms
Eutrophication	Excesses nutrients in water encouraging the growth and decomposition of oxygen depleting plant life
Geomophic	Of or relating to the form or surface features of the earth
Graminoid	Herbaceous plant with a grass-like morphology
Heterogeneous	Diverse in content, consisting of different parts or things
Heterotrophs	Organism obtains nourishment by digesting plant or animal matter
Hydroperiod regime	Seasonal pattern of the water level
Humification	Measure of organic decay
Lake marl	Lime rich mud in the form of calcium carbonate
Latent heat	Heat required to change the state of a material (from solid to liquid or liquid to gas) without change of temperature
Limnology	Aquatic ecology
Macropore	Cavities larger than 75 µm
Microhabitat	A small habitat within a larger habitat, that possesses unique properties and conditions
Minerotrophic	Water supply from streams or springs
Mire	Any peat forming wetland (bog or fen)
Morphology	A particular form, shape, or structure
Ombrotrophic	Water supply from precipitation
Palaeoecology	Study of fossil animals and plants
Paludification	Process of boreal landscape change to the formation of peatlands
Peat	Soil that consists of partially decomposed plant material which is formed *in-situ* under waterlogged anaerobic conditions
Peatland	Land upon which peat forms
Permafrost	Soil, rock or sediment that remains at or below 0ºC for at least two consecutive years
Precipitation	Rain, snow, sleet, or hail that falls to or condenses on the ground
Redox	Short for reduction-oxidation reaction, chemical reaction in which the oxidation state of atoms are changed
Rhizodeposition	Release of organic compounds from plant roots into the rhizosphere
Rhizosphere	Region of soil in direct connectivity with plant roots and soil microorganisms

Standard deviation	Square root of the variance and expresses how much the members of a group differ from the mean value for the group
Standard error	Standard deviation of the sample mean divided by the square root of the sample size
Terrigenous	Of a marine deposit, made of material eroded from the land

Acknowledgements

I would like to gratefully acknowledge the funding of this PhD studentship by Scottish Natural Heritage (SNH) and the Scottish Environment Protection Agency (SEPA). I would also like to acknowledge significant additional support received from Wildland Limited. The spectro::lyser and dissolved inorganic carbon instruments were purchased thanks to grant awards from the SNH Peatland Action Programme.

My greatest gratitude goes to my supervisor Dr Andrew Black; his enthusiasm and devotion towards his hydrological research alongside the dedication and kindness shown to his students is truly inspiring.

I would like to thank Dr Mark Cutler who took over as my second supervisor in the third year of the project. Thanks also to Dr Tom Ball who supervised the first two years and continued to offer advice throughout the project. I am also grateful to my SNH supervisor, Dr Andrew Coupar for his expertise and supervision. Many thanks to Dr Olivia Bragg for her support and guidance; I valued your input and knowledge which you contributed throughout the project.

To the rest of the University of Dundee Geography department (including Alan Long, Craig Phillips, Anne Coats and Sandra Arnot): “it is good people who make good places” so a thank you to you all. Thank you to the Centre for Ecology and Hydrology (CEH) at Bush Estate for the use of laboratory equipment. To Finlay Leask for his help with data QA and to the examiners whose contributions have helped shape this final submission.

To Glenfeshie Estate and the landowner Mr Anders Holch Povlsen, this project would not have been possible without your support. To Thomas MacDonell (Director of Conservation and Forestry) for his insightful supervisory input and hands on help provided. Thanks to Wes, Davie and the rest of you for being so welcoming, accommodating and supportive during a fair few visits over the years.

‘Some people make the world special just by being in it’, Mum, Dad for me that is the both of you. Such caring, loving, kind-hearted people and I am thankful every day for all you do for me.

To the person I love spending time with, Jamie you are part of the reason I am where I am today and I look forward to seeing where life takes us in our next chapter together.

Declaration

Candidate – Emma Louise Bryder

I hereby declare that I am the author of this thesis: that the work of which this thesis is a record has been done by myself, and that it has not previously been accepted for a higher degree.

Sign:

Date: 12/04/2020

Word count (including abstract, figures, tables, reference list, and appendices): 106,126

Abstract

Healthy, functioning peatlands are a net carbon sink and are a globally important terrestrial carbon store alongside numerous other wider ecosystem benefits. Degradation of peatlands by unsustainable management and erosion can increase emissions of carbon dioxide (CO_2) and methane (CH_4). Peatlands are also a principal source for dissolved organic carbon (DOC) loss to the fluvial environment and water discolouration. Understanding of the aquatic carbon budget is important in terms of policy and anthropogenic climate change mitigation in today's society.

The Mòine Mhór (900-950 m) is an upland blanket bog located in the north-west of the Cairngorms National Park, Scotland. It is currently in poor condition with 242 ha of bare peat located within the 1600 ha study site, equating to 15 % bare peat coverage. This study aimed to further the understanding of the variations in catchment characteristics and water chemistry between eight streams monitored on the Mòine Mhór plateau.

Through a nested design to capture data using continuous monitoring systems, grab sampling and flow monitoring, the hydrology of the peatland in relation to river flow was analysed. It was found that there were no significant differences between the monitored streams in relation to the catchment specific conditions and water chemistry parameters recorded (pH, absorbance, conductivity, dissolved oxygen and suspended sediment). Small variations were evident, such as the lower absorbance values for the Garbhlach catchments which were less eroded than the Caochan Dubh catchment. When taking into consideration all the monitored streams, a greater extent of bare peat within the catchments did not significantly correlate with the largest DOC exports. Overall, the larger stream catchment areas had higher mean DOC exports (2.7 – 2.8 gC/m^2) than when compared to the values from the smaller stream catchments monitored (0.5 gC/m^2). However, there was a significant positive correlation between water quality parameters and flow rates across the monitored catchments. The aquatic carbon budget at the Mòine Mhór south east tributary was quantified by use of the data collected from a spectro::lyser, which indicated a carbon export of 35.5 $gC/m^2/yr$. Flux estimates of annual DOC export from the Mòine Mhór were 28 gC/m^2 which is representative of a typical peatland headwater catchment. This equates to a total carbon loss through runoff over the area of 31 tonnes of carbon per year.

The key processes affecting the aquatic carbon export from the Mòine Mhór study site were summarised in a conceptual model. The main processes related to flow pathways, seasonal climate and vegetative cover. Deer are also a large contributor to the condition of the site and require ongoing management should restoration take place at this site. The benefits associated with restoring the site include its designated status, prominent location within the Cairngorms National Park and the carbon emissions that will be saved by halting or reversing the currently eroding Mòine Mhór peatland.

Keywords: peatlands, blanket bog, carbon, catchments, erosion, deer

1. Introduction

1.1 Project rationale

Peat is a type of soil that consists of partially decomposed plant material which is formed *in-situ* under waterlogged anaerobic conditions (Charman, 2002). The land on which the peat forms is classed as a peatland identifiable by the depth and organic matter content of the material formed. Although many variances exist between disciplines and countries, the definition of a peatland universally requires a minimum depth of 0.30 metres (m) and an organic matter content greater than 30 % (Joosten and Clarke, 2002; Montanarella *et al.*, 2006; Agus *et al.*, 2011).

Peatlands are important for a number of reasons from biodiversity to the storage of carbon, water quality, preservation of a historic environment, flood control and they form an important part in landscape diversity (Joint Nature Conservation Committee, 2011). This project aims to quantify the freshwater carbon fluxes within an area of peatland that is currently in poor condition, thereby inhibiting its capacity to carry out these essential functions. A type of peatland relevant to this study is the highly acidic blanket bogs which form as the peat spreads out over the landscape. Blanket bogs are found in cold climates with high rainfall and humidity levels (Labadz *et al.*, 2010). The terms peat, peatland and more specifically blanket bog are referred to throughout this thesis. The material is referred to as 'peat', the land upon which peat is formed will be referred to as the 'peatland' and more specifically 'blanket bog' which refers to an upland rain-fed peat accumulation.

1.1.1 Global importance of peatlands

Globally, peatlands store 550 gigatonnes (Gt) of carbon making them an important carbon store (Barthelmes *et al.*, 2015). In terms of the ecosystem, peatlands cover 3 % of the terrestrial land surface and store twice as much carbon as that stored in forest biomass (Strack, 2008). Once overlooked and described as the 'Cinderella habitat' peatlands are now increasingly recognised and valued for the intrinsic ecosystem benefits they provide to the environment, society and the economy (Table 1-1) (Bain *et al.*, 2011; Marsden and Ebmeier, 2012). Scientifically, attention has primarily focused on the blanket and lowland bog habitats of the northern hemisphere. However, less well known but still as important is the recognition that peatlands are present in many landscape areas such as in the tundra environment or in peatland rainforests.

Table 1-1: Benefits provided by peatlands if in a healthy state and pressures placed on peatlands

Development could include the construction of windfarms or roads on peatlands. Inspired from; Marsden and Ebmeier (2012).

Benefits	Pressures
Ecosystem services	Drainage
Carbon sink	Burning
Unique habitat	Over grazing/trampling
Biodiversity	Pollution
Specialised flora and fauna	Cutting/extraction
Water quality/drinking water	Development
Flood risk management	Vehicles/walkers
Historical archive	Erosion
Local heritage	Peatland fires
	Drought
	Acid rain
	Climate change

The preservation of peatlands has been recognised as important to maintain the future health of this finite resource. The accumulation of peat is a slow process with a growth rate of 0.5 - 1 mm per year making it a temporally and spatially sensitive habitat (Verhoeven *et al.*, 2006). Unfortunately, due to pressures from land management and human induced climate change, 25 % of the world's peatlands have already been destroyed (Parish *et al.*, 2008).

1.1.2 Peatlands and deer management in Scotland

Scotland, the location for this project, is known for its wet temperate climate which is ideal for peat formation. However, the peat is vulnerable to changes in climate and land use, which can alter the peatland hydrology and reduce peat accumulation rates (Chimner and Cooper, 2003; Cooper *et al.*, 2015; Hribljan *et al.*, 2015). The shared aim and vision of how to achieve peatland policy, research and management is outlined in Scotland's National Peatland Plan (Aalders *et al.*, 2011; Scottish Natural Heritage, 2015). The National Peatland Plan looks forward to the future of Scotland's peatlands which involves protection and enhancement of our national asset ultimately benefiting all of society (Scottish Natural Heritage, 2015).

It is estimated that 70 % of Scotland's blanket bogs are damaged to some degree and high deer numbers can have negative impacts on this particular habitat due to overgrazing and trampling (Scottish Natural Heritage, 2015). In relation to conservation, the deer population is controlled in some locations in order to limit the impacts of overgrazing, trampling and browsing on vegetation. The deer can negatively affect the regeneration and biodiversity of the country's sensitive and diverse uplands if not suitably managed (Scottish Natural Heritage, 2015). Therefore, management of the deer population through human intervention is essential in Scotland, as the deer have no remaining natural predators (Mitchell and McCowan, 1986; Putman *et al.*, 2005; Pellerin *et al.*, 2006; Scottish Natural Heritage, 2016a). Wild deer are an important natural asset to Scotland's countryside with regular sustainable culling carried out in order to achieve a healthy sustainable population.

The over population of deer is predominately a problem in the United Kingdom (UK) and United States in a global context, where the lack of natural predators and adaption to a variety of biomes has allowed the expansion in numbers (Leopold *et al.*, 1947; Stromayer and Warren, 1997; Côté *et al.*, 2004; Warren, 2011). Britain has the greatest European population of red deer and where red deer are present, they tend to thrive (Butzler, 1986; Hmwe *et al.*, 2006). As a result of the thriving deer population, these mammals have an important role to play when considering the future management of the peatland ecosystem.

1.1.3 Designated land in Scotland

Scotland has a land area of 78,800 km^2 and is well renowned for its image as containing beautiful and pristine wilderness areas, with a tourist trade worth £5 billion per annum (Warren, 2009). Over half the country is made up of the uplands with 284 peaks recognised as 'Munros' (>3000 ft. or >914 m) (Warren, 2009). The uplands, inclusive of the mountains are classified as lying 'typically above the limits of enclosed farmland' and cover two thirds of Scotland's land (Plantlife, 2010) with one third of the uplands made up of blanket bogs (Horsfield and Thompson; Scotland's Environment, 2014). The importance of

Scotland's uplands is recognised in the extent of nature designations upon it; 24 % lies within Special Protection Areas (SPA), 16 % in Special Areas of Conservation (SAC), 22 % in Sites of Special Scientific Interest (SSSI), 11 % in National Parks and 3 % in Natural Nature Reserves (NNR) (Scotland's Environment, 2014).

1.1.4 Peatland policy and funding sources

Money, time, scientific research, and resources have been invested into peatlands to protect and restore one of Scotland's most important habitats. A theme to come out of a recent conference focusing on the delivery of peatland restoration and management highlighted the importance of partnership working (International Union for Conservation of Nature, 2017). For example, involving the 'local public' in the decision-making process surrounding peatland management would add value to the partnership.

The third report on policies and proposals for meeting greenhouse gas (GHG) emission reduction targets from 2018-2032 is outlined in the Scottish Government's Climate Change Plan (CCP) (Scottish Government, 2018). Upon searching the CCP the phrase 'peat' is mentioned 88 times and more specifically 'peatland restoration' is mentioned 20 times highlighting the significance of peatlands from the perspective of the Scottish Government reducing GHG emissions. With regards to knowledge exchange within the political sphere, the ClimateXChange is a valuable and useful vehicle for policy makers (Scottish Government and Scottish Natural Heritage (SNH)) to inquire about the current scientific position of the main research providers and others, inclusive of Dundee University, on assorted climate change policy topics such as 'Carbon Savings from Peat Restoration' (Chapman *et al.*, 2012; ClimateXChange, 2017).

In relation to funding, the Scottish Government allocated £5 million to SNH in a Green Stimulus Package in 2012, which was used to implement the Peatland ACTION project (Scottish Natural Heritage, 2016b). The deliverables included peatland restoration, enhanced ecosystem resilience to climate change and to increasing others' understanding of our peatlands (Scottish Natural Heritage, 2016b). To sustain the effort, a further £3 million was announced by the Scottish Government in 2015 for peatland restoration work, in addition to the

£10 million made available under the Scottish Rural Development Programme (SRDP) in 2015 (The Scottish Government, 2015; Scottish Natural Heritage, 2016b). The Scottish Government has proposed restoration of 50,000 hectares (ha) of peat by 2020 with an estimated 600,000 ha of degraded peatlands in Scotland (Scottish Natural Heritage, 2015). Since 2013, as a result of Scottish Government funded action supported by SNH, more than 10,000 ha of degraded peatland have been restored. This is currently below the target however this trend is set to continue as targets keep increasing year on year with a step change required in the approach in order to reach the ambitious targets (Scottish Natural Heritage, 2017a). Other sources of funding for peatland restoration include the private sector and other European sources with crowd funding also highlighted as a new avenue to explore (Artz *et al.*, 2013). As an example, with reference to a rewilding journey for Scotland; Trees for Life currently have a successful crowdfunding page that has raised over £25,000 from the donations of over 400 supporters so far (Crowdfunder LTD, 2018).

1.2 Justification of study

Since peatlands are a great carbon store for the planet, the rationale and interests underlying this project are to further understand the extent and condition of an upland blanket bog and quantify the aquatic carbon fluxes from the study site. Scotland has the ideal wet temperate climate required for peatland formation with blanket bogs covering up to one third of Scotland's upland habitat (Horsfield and Thompson; Scotland's Environment, 2014). This project will be focused in Scotland where around 70 % of the blanket bogs are damaged to some degree (Scottish Natural Heritage, 2015). Scotland's Climate Change Plan focuses on peatland restoration as a means to restoring these damaged habitats. Overall, this project will contribute knowledge and research into the area of uplands, peatlands and deer management in Scotland. The project rationale is topically relevant in terms of policy and anthropogenic climate change mitigation in today's society. More specifically, this research project contributes to the base of knowledge that leads to and supports the Scottish Government's decision to propose policy measures that relate to peatland restoration.

1.3 Aims and objectives

The aim of this research is to assess the aquatic carbon fluxes of a high altitude peatland and monitor the spatial variability of peatland extent, condition and water chemistry within and between the Glenfeshie Mòine Mhór sub-catchments. To fulfil the aim, the following two objectives have been set:

- Characterise and explain variability and patterns of dissolved organic carbon and other parameters with reference to flow, event, seasonal and annual timescales; and

- Characterise variations between the eight sub-catchments of the Mòine Mhór and explore causal factors which may be responsible for the spatial differences observed.

It is hoped that this work will have a broader far reaching applicability to the study of other eroded peatlands in high altitudes and make a beneficial contribution to the field of peatland ecohydrology and management. It is anticipated that this research on 'Britain's highest bog' will contribute new baseline knowledge of peat condition and processes ongoing at the site. This knowledge will help inform on how best to move forward with the site management and provide monitoring results which are currently lacking from arctic/alpine peatland sites. This project is part of a wider research interest in the Feshie catchment area where hydro-meteorological monitoring has been carried out since 2002. An outline of subsequent chapters is provided in the next section.

1.4 Thesis outline

Chapter 1 introduces the research topic and provides the context for the research and sets out the aims and objectives for the project. Chapter 2, following on from this section, draws on an extensive range of academic and other literature to identify what is known and where the uncertainties are whilst critically reviewing the research topic. Chapter 3 introduces the unique area of study and Chapter 4 highlights the field and laboratory methods used to achieve the aims and objectives of the project. Chapter 5 presents the results of the project whilst Chapter 6 is a discussion of the results in relation to the aims and objectives set. Chapter 7 presents the limitations and future research recommendations, finishing off with the concluding remarks.

Throughout the thesis it is proposed that the content makes a unique contribution to a detailed study of the streams draining a high altitude eroded peatland site in Scotland. It is acknowledged that this is a small scale detailed study of a catchment area over a three year time scale but it hoped that the findings can be extrapolated to other catchments where similarities may lie.

2. Literature review

This literature review focuses on the formation of peatlands, the hydrology, ecology and carbon budget associated with a functioning peatland followed by the management and restoration activities associated with eroding peatlands. Peatlands are a living landscape which have been subject to different pressures and uses from their development. The research undertaken in this project is on an upland blanket bog called the Mòine Mhór, located in the Cairngorms, within the eastern Highlands of Scotland. The Mòine Mhór has been subject to erosion pressures linked to the montane environment and land management (Evans, 1971; Grieve *et al.*, 1995; Crabtree and Bayfield, 1998). The primary focus of the study is on catchment freshwater carbon fluxes, which are looked at in relation to other interacting topics of relevance to the study site, namely erosion, deer and land management. The study site refers to the area of the Mòine Mhór plateau and is referred to as "the study site" or the "Mòine Mhór" throughout the thesis.

2.1 Peatland classification

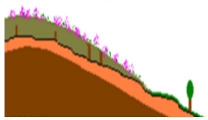
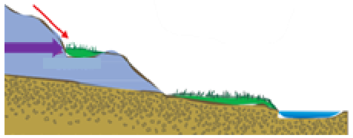
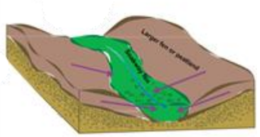
Globally, there are various types of peatlands that are described and classified according to their area and carbon storage (Milne and Brown, 1997; Joint Nature Conservation Committee, 2011). Peatland is the term used to describe an area of land which is persistently waterlogged, leading to the establishment of distinctive bog habitat and the formation of organic rich peat soils. Bogs and fens are the two predominant peatland types located in the UK (Joint Nature Conservation Committee, 2011). Bogs receive their water supply from rain, snow or mist while fens receive surface runoff and/or groundwater as well as direct atmospheric precipitation. Bogs can be classified as blanket bogs or raised bogs (Table 2-1). Fens may be classified as basin fens, valley fens or sloping fens (Table 2-1) (Charman, 2002; Wheeler *et al.*, 2009).

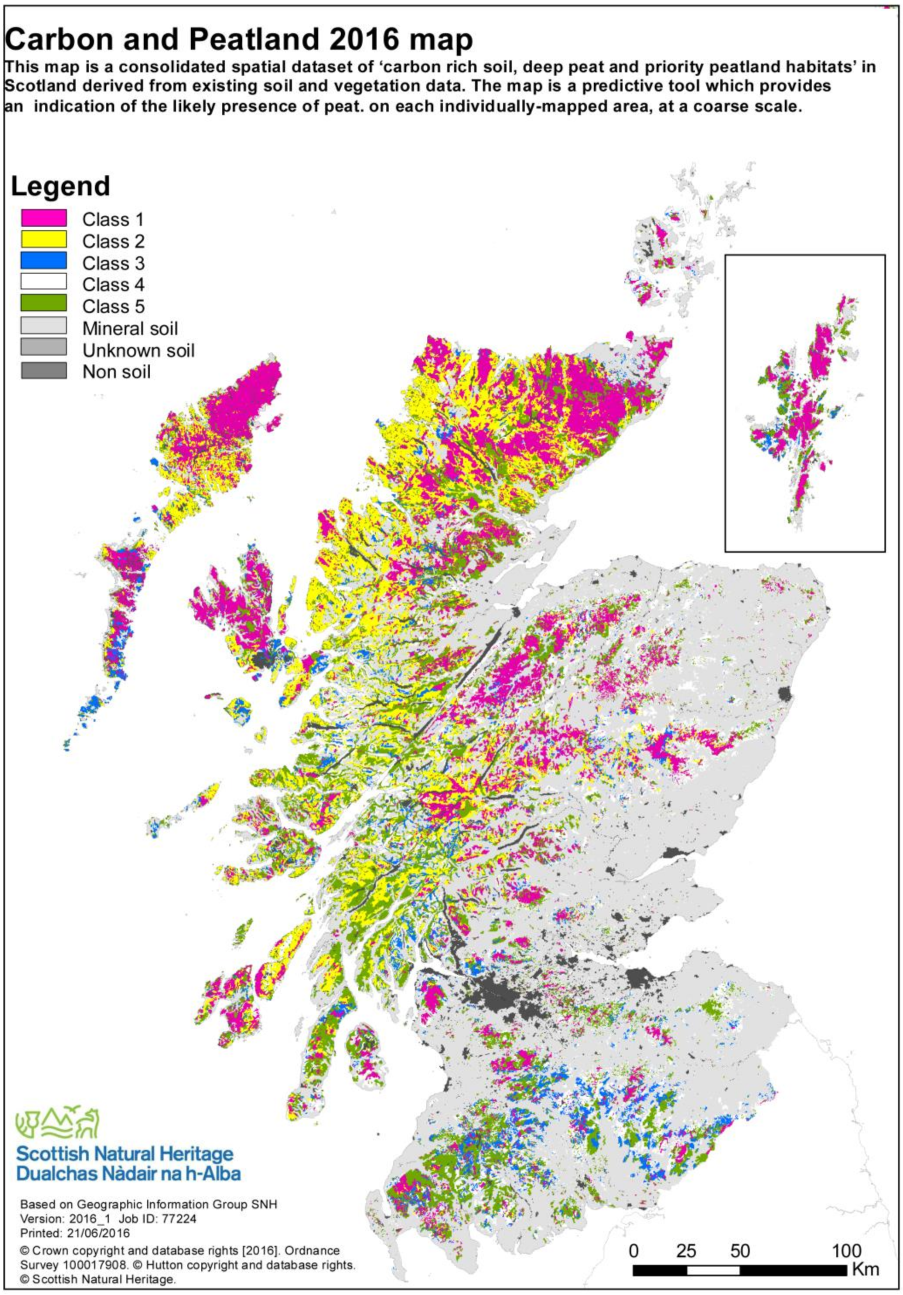
The Soil Survey for Scotland classifies organic soils (peat) as a surface layer or layers with a depth greater than 0.5 m thick and containing more than 60 % organic matter (Figure 2-1) (Soil Survey of Scotland Staff, 1984; Forestry Commission, 2016; Scotland's Environment, 2017). To highlight some of the difference in classifications, the Soil Survey for England, Wales and the British

Geological Survey use a shallower depth of 0.4 m to classify peat (Avery, 1980; Cranfield University, 2017).

Table 2-1: Comparison between the main peatland types found in the UK

There is no strict boundary between bog and fens and they can occur side by side. A fen may also transition into a bog resulting from the build up of peat over time which separates the fen from its groundwater and nutrient supply. Inspired from; (Aalen *et al.*, 1997; Abbot, 2001; McBride *et al.*, 2011; United States Department of Agriculture, 2017).

Peatland	Bogs		Fens		
Type	Blanket	Raised	Basin	Valley	Sloping
Size	Expansive	Small	Small	Large	Small
Location	Wet/upland areas	Lowland areas	Near/on open water	Floodplains	At/on moderate to shallow slopes
Appearance	Homogenous	Dome	Flat	Mosaic habitat	Herbaceous/ graminoids
Characteristics	Acidic – low nutrients – specialised community		Less acidic – higher nutrients – diverse community		
Hydrological regime	Water received predominately from precipitation Outflow primarily to groundwater		Water received mostly from surface and groundwater sources Outflow by surface and subsurface pathways		
Schematic	 *Abbot., 1997*	 *Abbot., 1997*	 *McBride et al., 2011*	 *McBride et al., 2011*	 *McBride et al., 2011*
Development	Peat blankets land preventing water leaving the surface (paludification)	Peat builds up and fills lake/pond (terrestrialisation)	Forms in glacial hollows – originally lakes/pond	Water supply from central watercourse and seepage from sloping areas	Maintained groundwater flow from landscape above



Legend	Description
Class 1	All vegetation cover is priority peatland habitats; all soils are carbon-rich soils and deep peat.
Class 2	The vegetation cover is dominated by priority peatland habitat; all soils are carbon-rich soil and deep peat.
Class 3	Vegetation cover does not indicate priority peatland habitat, but is associated with wet and acidic soil types; most soils are carbon-rich soils, with some areas of deep peat.
Class 4	Area unlikely to be associated with peatland habitat or wet and acidic soils; area unlikely to include carbon-rich soils.
Class 5	Soil information takes precedence over vegetation data; no peatland habitat recorded; may also show bare soil. All soils are carbon-rich soil and deep peat.

Figure 2-1: Distribution and classification of peatland habitat across Scotland

The colours in the map correspond with the descriptive legend table (Scottish Natural Heritage, 2016c; d). Most of the peatland habitat occurs in the north and west of Scotland given the suitability of the climate for peatland development in these areas. The islands at the north west coast of Scotland and the Outer Hebrides largely comprise of Class 1-3 peatland habitats.

2.2 Peatland formation

Blanket bog covers approximately 7.5 % (22,500 km^2) of the British Isles (Tallis, 1998). Blanket peat develops in high precipitation areas, typically associated with the uplands. Areas of relatively flat or gently sloping terrain support the waterlogged conditions required for the initial spread of blanket bog habitat and peat can form in shallower depths at slopes of up to 40° (Warburton, 2003; International Union for Conservation of Nature, 2014; Irish Peatland Conservation Council, 2017). The formation of peat is controlled by an interaction of climatic conditions, hydrological, geological and geomorphic factors (Jinsheng, 2009).

2.2.1 Peatland timeline

Climatic, geological and geomorphic factors such as the coverage of the Northern Hemisphere by glaciers in the Pleistocene have influenced the formation of peat. The end of the last glaciation period around 13,000 years ago left behind a very uneven landscape of ridges and hollows throughout the country. This created a micro-topographic change in the landscape that was important for the development of peatlands. The hollows, many with poor-draining soils, accumulated water and formed a large number of smaller waterbodies commonly referred to in the literature as lakes (Charman, 1994; Barron *et al.*, 2011; Kirkbride *et al.*, 2014). When the climate warmed, vegetation grew in the lakes in a process known as infilling (Figure 2-2) (Rydin and Jeglum, 2013).

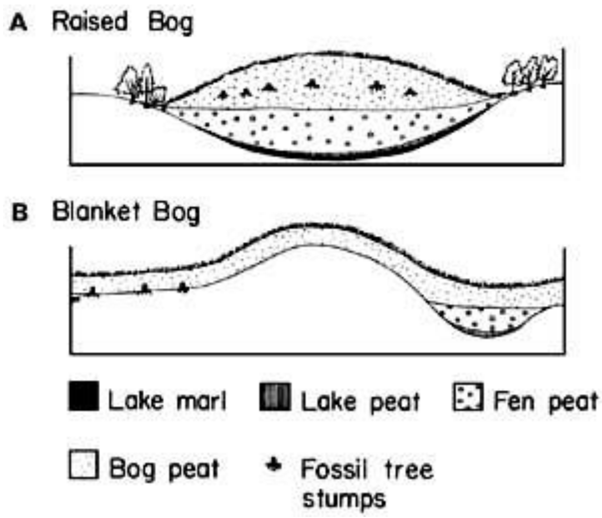


Figure 2-2: Raised bog (A) and blanket bog formation (B)

The retreat of the glaciers left behind shallow lakes and eskers which trapped the water. Deposits of lake marl overlying clay and glacial drift sat alongside these lakes. Reeds and sedges fell into the water collecting as peat on the lake bed, over time adding to the accumulating fen peat. Transition into bog habitat resulted from the increasing depth of peat separating the plants from the calcium rich groundwater creating the raised bog and blanket peatland habitats displayed above. The fossil pine tree stumps seen above resulted in a period of drier weather that resulted in the establishment of woodland on the ground surface. The tree stumps were buried and preserved in the peat upon wetter weather returning. Source: Irish Peatland Conservation Council (2002).

The climate fluctuated from very warm and dry, sediment left behind from the glaciers were colonised by pioneer plant species and forests also established. Then it became wetter and colder and around 8,000 years ago the trees died away. The treeless soil then became waterlogged and infertile creating the expanse of the blanket bog landscape seen today (Figure 2-3) (Tallis, 1991; Crawford *et al.*, 2003). The peatland landscape described can be found in the boreal ecosystem, which refers to the region of the Northern Hemisphere with a subarctic climate (Limpens *et al.*, 2008).

2.2.1.1 Paludification

The process of boreal landscape change from forest to peatland is known as paludification. One of the most dramatic landscape changes took place in northern Scotland at the beginning of the Neolithic period around 6,500 years ago (Bastian and Steinhardt, 2002). The start of the Neolithic farming period saw a visible change in the substitution of trees by heathlands and peatlands. This change was most striking in oceanic areas such as Orkney and Shetland, western Norway and the Hebrides when compared with more continental areas (Bennett *et al.*, 1992; Odgaard, 1992; Tipping, 1994; Bunting, 1996; Crawford *et* *al*., 2003). The reasons as to why there is a marked difference between these areas remains a topic of investigation, one suggestion is that grazing opened up the tree canopy in the oceanic areas (Crawford *et al*., 2003). Tree removal had started with the post-hypsithermal which saw a change to wet cool summers after the Hypsithermal warm period. The climatic changes and loss of trees resulted in water table rise and paludification, creating the peatland habitat seen today (Crawford *et al*., 2003).

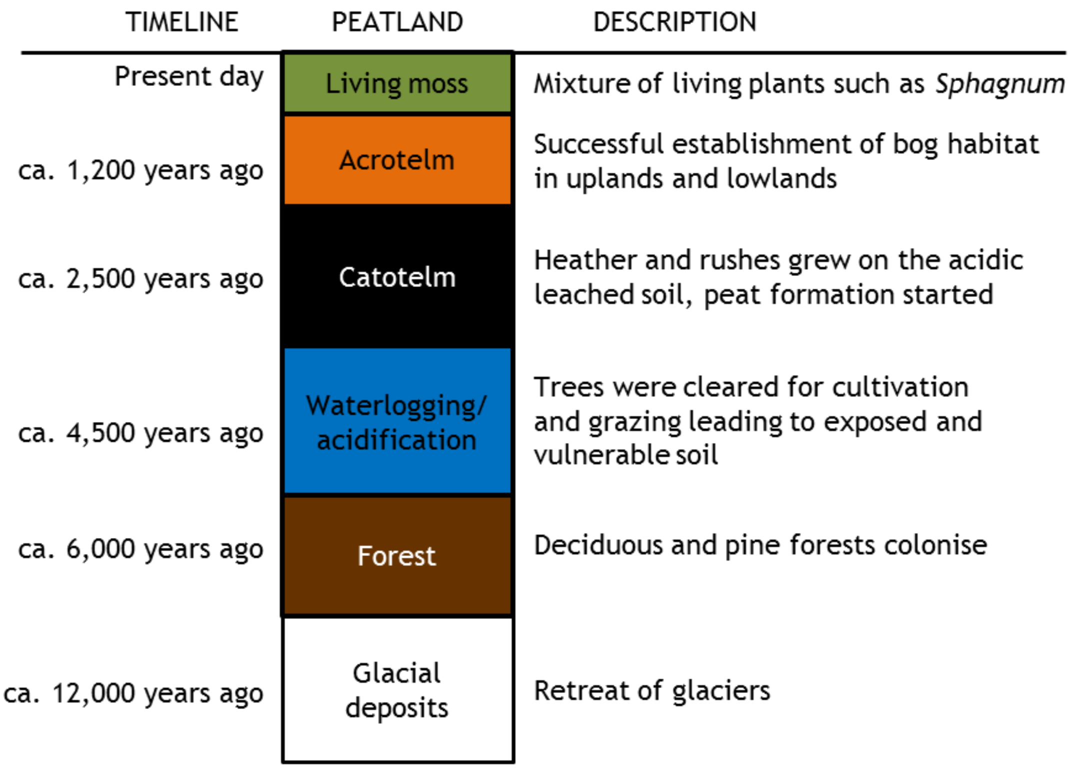


Figure 2-3: Peatland calendar for Britain

Forests covered vast areas of the landscape after the retreat of the glaciers. The forested areas were cleared for cultivation and grazing opportunities. The soil was exposed and vulnerable to the leaching of nutrients, in turn causing it to become more acidic. Leached minerals were deposited at a lower level obstructing drainage causing areas to become waterlogged. Heathers and rushes grew on the acidic leached soil commencing the start of peat formation. The acidic and waterlogged conditions around 2,500 years ago were suitable for peat formation (Bord na Móna, 2017). The living moss and acrotelm are the layers in which the peat is formed and the catotelm is the lower layer of peat deposited. Inspired from; Bord na Móna (2017).

2.2.2 Controls on peat formation

As well as the suitable environment, a number of conditions are required over a long period of time for peat growth. The controls on blanket bog formation include: continuous annual growth of vegetation, moderate-high precipitation, low temperatures, a low level of evapotranspiration, waterlogged soil and anaerobic conditions (Gallego-Sala *et al.*, 2016; Bord na Móna, 2017). The conditions required for peatland development include: precipitation of at least 700 – 1000 mm per annum and 150 – 175 rain days per year for raised bogs and precipitation of >1250 mm per annum and >200 precipitation days per year for blanket bogs, a monthly mean temperature of less than 15 °C and an annual water surplus (Lindsay *et al.*, 1988; Bord na Móna, 2017).

In areas of blanket bog habitat in the UK, between the months of April and September, the excess evapotranspiration was over 200 mm (Stroud *et al.*, 1987). The UK has a relatively wet climate, which has been important in the evolution of peatland development (Figure 2-4). The combined climatic conditions of water and temperature favour the development of peat by positively influencing the growth of vegetation and limiting the activity of soil microbes (Jinsheng, 2009). The blanket bogs increased in depth as *Sphagnum* moss reduced the bacterial breakdown of plant remains beneath the surface leading to peat formation. The topography of the British Isles allowed the peat to grow on all but the steepest of slopes (Lindsay *et al.*, 1988).

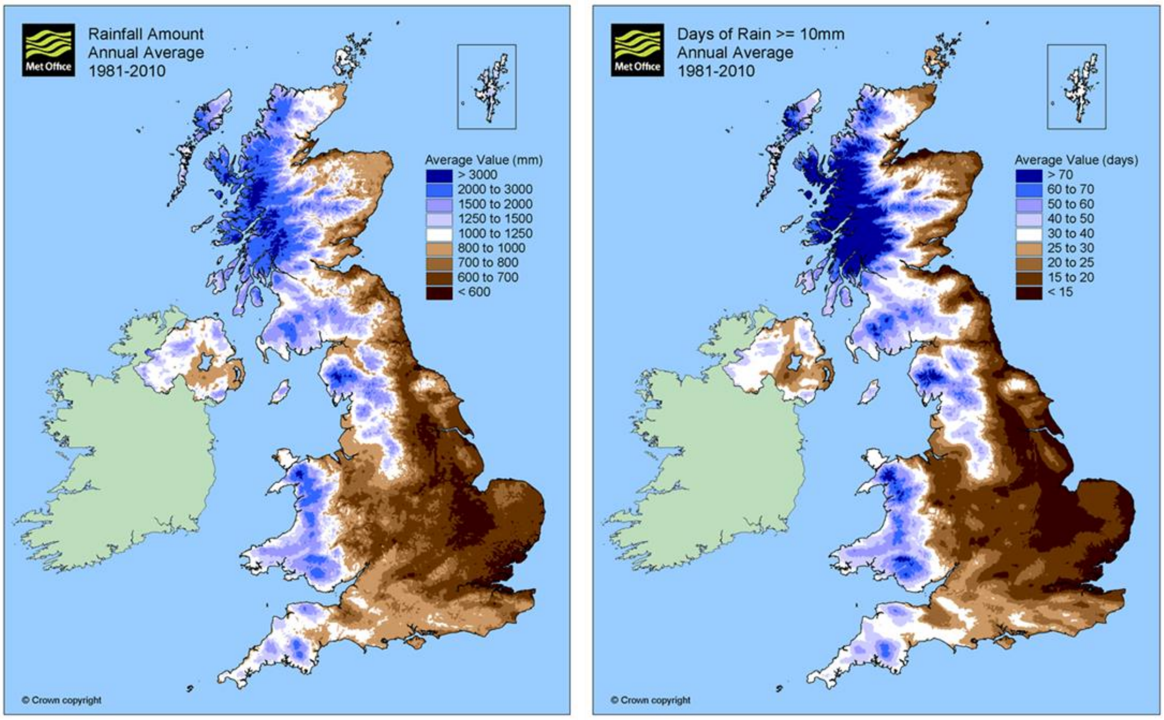


Figure 2-4: Annual mean precipitation and precipitation days 1981 - 2010

Left - Mean annual amount of precipitation (mm). *Right* - mean number of days of precipitation (≥ 10 mm) across the UK. The annual mean precipitation from 1981 – 2010 displays the drier eastern and southern areas of the UK in comparison to the wetter areas highlighted in blue across the western coast. The west coast areas have been previously indicated as more suited to the development of peatland habitat (Figure 2-1) attributable to the precipitation data presented. Source: Met Office (2017a). *Note the terminology of precipitation has been used as it includes rain, snow, sleet, and/or hail that falls to or condenses on the ground.*

2.2.2.1 Peat biogeochemistry

The way in which peatlands form and develop through the decomposition of organic material means that a physical fossilised record is maintained of the past vegetation and climate of the area upon which they were located. Techniques such as radiocarbon dating, tephrochronology, macrofossil analysis and pollen analysis can be used to determine the past environment and date when changes may have occurred. Peat geochemistry is now widely used with stable lead isotope analysis in order to reconstruct historical environmental climate and land use changes (Bindler, 2006). Lead isotopes (^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb) can be used to identify the main sources of lead incorporated into the peat bog during differing time periods, allowing the reconstruction of events that took place in climate and land use over time (Shotyk *et al.*, 2001). Over a decade ago, scientists dug a 650 cm core from a raised bog called Etang de la Gruère, located in the Jura Mountains of Switzerland, representing 12,370 ^{14}C years of peat accumulation. This study gave the best quantified and most complete record of peat geochemistry in Europe (Bindler, 2006). The isotopic analysis assisted in the finding that all the lead deposited throughout the Holocene was delivered solely from the atmosphere (Shotyk *et al.*, 2001).

Biogeochemical processes can be used to understand the effect and transport of elements and compounds that occur in peatlands, either naturally or through anthropogenic sources. This allows researchers to identify the origins of material within the peat. The peat fluvial geochemical record consisting of sedimentary deposits taken from the peat can be used as a tool to answer various research questions relating to time, for example; the history of ancient mining and the reconstruction of anthropogenic atmospheric pollution (Mighall *et al.*, 2002; Monna *et al.*, 2004). The geochemical techniques combined with palaeo-botanical and field archaeology supplied an effective tool in understanding the interaction of *Homo sapiens* in relation to early mining and smelting with a particular focus on blanket bog uplands. The use of the geochemical records stored in peatlands to understand the past environment and climate has increased over the years (Bindler, 2006).

A number of studies have been carried out on the biogeochemical processes of peatlands in temperate regions (Shotyk, 1998; Mandernack *et al.*, 2000). Geochemical data allows the difference between the ombrogenic zone (atmospheric inputs) and the minerogenic zone (atmospheric inputs plus soil, sediment and water interactions) of peat bogs to be determined (Shotyk, 1998). Depositional patterns on a small-scale can be influenced by microtopography and possibly vegetation which is connected to the biochemistry within the peat (Bindler, 2006).

Connecting isotopic tracers with high frequency monitoring of dissolved organic carbon (DOC) was used as a method by Tunaley and colleagues in 2017 to improve understating into the hydrological connectivity and runoff generation processes influencing the amount of DOC ending up in the stream. It was found that high hydrological connectivity between the DOC sources and the stream is important in mobilisation within the riparian zones of upland peatland dominated catchments. This process results in high DOC concentrations at the peatland site during baseline (~5 mg l^{-1}) in comparison to the larger scale catchment with a reduced riparian peatland cover (~2 mg l^{-1}) (Tunaley *et al.*, 2017). Constant seepage from the peatland was found to sustain high baseflow at the headwater scale even during low summer flows (Tunaley *et al.*, 2017).

2.2.3 Peatland structure

Peat is a three-phase porous medium: the structure is solid, while the voids may be filled with water, air or both (Loisel *et al.*, 2013). The acrotelm-catotelm peatland bog development paradigm was defined by Ingram in 1978 and includes two soil layers; acrotelm (high peat saturated hydraulic conductivity, intermittently water logged) and catotelm (low peat saturated hydraulic conductivity, permanently water logged) (Figure 2-5) (Ingram, 1978). This view of the surface hydrology of peatlands still remains to date the most widely accepted.

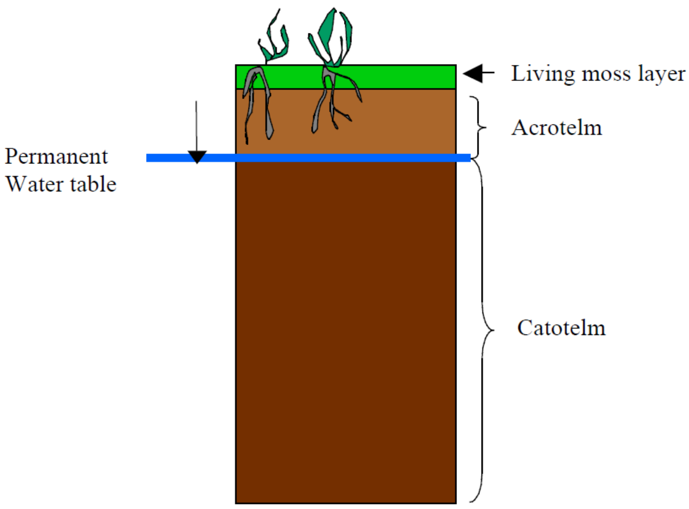


Figure 2-5: Peatland soil layers

Schematic representation of peatland soil layers highlighting the living moss surface layer with the acrotelm at 0.2-0.8 m (Scottish Renewables et al., 2010). The acrotelm stabilises the fluctuations of the water table and the catotelm which is described as the lower amorphous peaty layer that is permanently waterlogged and anaerobic at a depth ranging between 1-10 m. Source: Scottish Renewables *et al.*, (2010).

The boundary between the acrotelm and catotelm is a gradual change from less decomposed to more decomposed peat. For hydrological purposes, the conceptual model by Ingram, while useful, is a little too simplistic (Whitfield *et al.*, 2009). Hydrological models that assign different parameters e.g. hydraulic conductivity as described in Letts and colleagues (2000) to the two layers in an abrupt boundary change can result in unrealistic hydrological simulations (Letts *et al.*, 2000; Whitfield *et al.*, 2009). The SIMGRO model (SIMulation of

GROundwater and surface water levels) was created to understand the groundwater system in peatlands and assist in their effective management (Querner *et al.*, 2010). As with other models it represents a simplification of the complex hydrological system. The model was capable of simulating stream flow and groundwater levels in three cases with differing land use and climatic conditions (Querner *et al.*, 2010). This highlighted the possibilities of the model to give estimates of the hydrological situation to help with peatland conservation.

In summary, the structure of peat comprises of a heterogeneous mix of more or less decomposed plant remains, water and trapped air (International Peatland Society, 2017). The morphology of peatlands is characterised by a water table at or near the land surface and vegetation which is adapted to these conditions.

2.2.4 Peatland growth

Modelling the growth and development of peatland layers was pioneered by Clymo in 1984. Ingram's acrotelm-catotelm model was a two-dimensional representation of a raised bog that investigated the influence of hydrology and water balance on bog cross-sectional shape and bog dimensions. Clymo also conceptually modelled peat growth and development based on the assumption that peat is produced in the acrotelm and decays after it is produced. Ingram and Clymo's terminology and concepts are both well known for contributing knowledge to the understanding of how peatlands function. The development of peat is controlled by a network of interacting feedbacks between the soil and water, vegetative cover and finally the biochemical properties of the soil, collectively termed as ecohydrology (Rodríguez-Iturbe and Porporato, 2004). The morphology of blanket bogs described by Clymo is diplotelmic (two layered) in profile (Clymo, 1984; Chambers, 2014). In the acrotelm-catotelm peatland bog development paradigm there are limits to peat bog growth coupling hydrology, ecology and carbon biochemistry (Figure 2-6) (Clymo, 1984).

Clymo's model made a step forward from the Ingram model furthering understanding in the behaviour and process of peatland development. However, the need to link Clymo's simplistic model for peat growth with interactions between ecology and hydrology has been more recently acknowledged to help further understand the effects peatlands have on the global carbon cycle (Belyea and Baird, 2006). The complexity of the adaptive peatland systems is displayed in the complex interactions between climate, soil and vegetation whist containing strong memory effects (Belyea and Baird, 2006; Waddington *et al.*, 2015). The peatland carbon cycle is globally significant, therefore in future research it is important to understand the complexities of peatland responses to predicted changes.

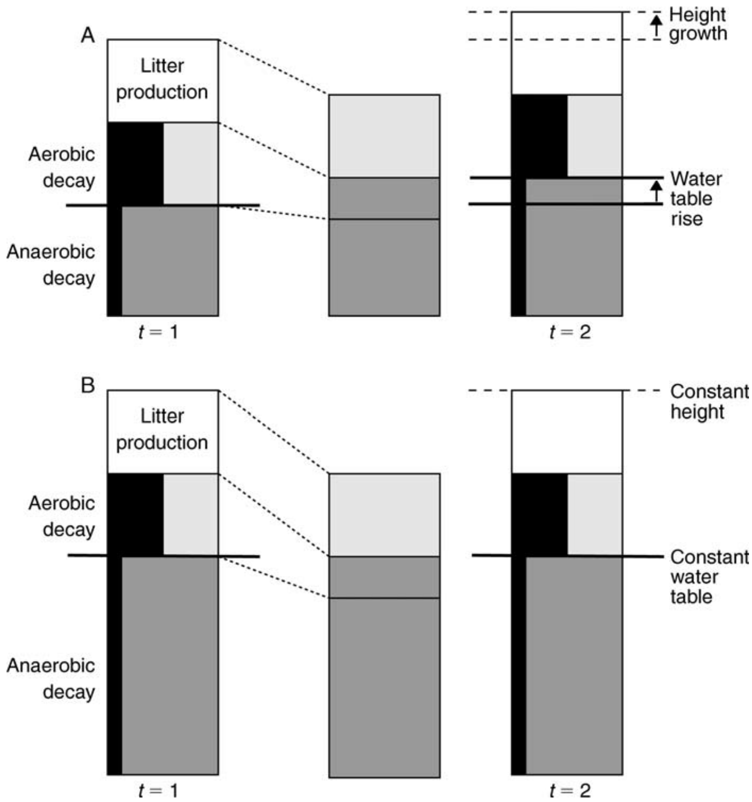


Figure 2-6: Schematic diagram of Clymo's 1984 model of bog growth

Cross sections are shown of the peat profile at observation time's t1 and t2, where t1 and t2 represent ongoing annual states during periods of growth. The amount of litter added is constant (white area), material in the acrotelm is shown in the medium grey area and the material in the acrotelm lost each year by aerobic decay is shown in the black area. The material in the catotelm lost each year by anaerobic decay is shown in the dark grey area. **A:** The bog grows in height as fresh litter production exceeds aerobic and anaerobic decay losses **B:** The bog maintains a constant height as fresh litter production equals decay losses. Source: Belyea and Baird (2006).

2.3 Peatland hydrology

2.3.1 Controls and drivers of peatland hydrological change

Change can be natural, in response to climatic conditions or influenced by human land management practices. The evolution of the river landscape is influenced by the scale and frequency of flooding (Gordon *et al.*, 2006). River behaviour can be controlled by factors such as the steepness of the river channel, the volume of water within the channel and the opportunity for sediment to be carried by the water (Gordon *et al.*, 2006). These factors dictate how much rivers can build up or erode their beds, the type of channel patterns and the potential for channel changes (Gordon *et al.*, 2006).

Since the introduction of the Water Framework Directive (WFD) (2000/60/EC), the focus on catchment based hydrology has increased. Since the introduction of the European Union (EU) WFD, research into peatland hydrology has furthered our understanding in relation to the controls and drivers of change, on the development of tools for monitoring and assessment whilst also looking forward to future impacts on peatland hydrology (Labadz *et al.*, 2010).

Topics relating to the controls on peatland hydrology include: water retention and subsurface flows (Querner *et al.*, 2010), water tables (Ferone and Devito, 2004), surface water runoff (Soulsby *et al.*, 2006), water quality (Soulsby *et al.*, 2002) and peat gully erosion (Wishart and Warburton, 2001). Findings about the drivers of change include the impacts on peatland hydrology of: drainage (Holden *et al.*, 2006), grazing (Clay *et al.*, 2009), burning (Worrall *et al.*, 2007a), afforestation (Lewis *et al.*, 2013), mechanised peat cutting (Seters and Price, 2002), construction (Grieve and Gilvear, 2008), grip blocking (Worrall *et al.*, 2007b) and scrub clearance (Lomas-Clarke and Barber, 2007).

2.3.2 Water supply in peatlands

Hydrological relationships play a key role in the lateral expansion of peatlands (Loisel *et al.*, 2013). The 1980s provided the first understanding of minerotrophic (water supply from streams or springs) and ombrotrophic (water supply from precipitation) northern peatlands (Siegel, 1983, 1988; Chason and Siegel, 1986; Siegel and Glaser, 2006). Technological advancement and application of new methods allowed the water movements within peatlands to be estimated by hydrologic measurements. This then brought about the application of groundwater hydrology research in peatlands. Investigating groundwater flows is three-dimensional making it more difficult to predict than surface water. Detailed investigation of groundwater flows requires use of methods such as pump tests and tracer studies on aquifer type and hydraulic conditions (Bartram and Ballance, 1996). These specialist investigative tests can help to aid in understanding the direction, rate of flow, quality and contaminant movements in groundwater.

Soulsby and colleagues utilised tracer data with catchment characteristics derived from a Geographic Information System (GIS) to increase understanding in catchment hydrology within the Feshie catchment. Groundwater contributions and residence times were both reduced in peat and/or shallow alpine soils and bedrock (~30 - 40 %, 2 to 5 months) in comparison to the more freely draining podzolic, sub alpine and alluvial soils (~45 – 55 %, 12 to 15 months) (Soulsby *et al.*, 2006).

With the development and decomposition of peatlands being dependent on their hydrology, peatland hydrology affects many receptors such as: nutrients, diffusion rates, redox status, species composition, carbon storage, water resource management, flooding, and stream water quality (Holden, 2005d). Consideration must be given to the temporal and spatial variability of hydrological processes to establish the results of environmental change on peatlands (Holden, 2005d).

2.3.3 Peatland microhabitat

Peatland hydrology including water table depth has an influence on peatland microhabitat. The surface of a peatland will be made up of a mosaic of different areas of habitat including pools, hollows, lawns and hummocks which may be thought of as the microhabitats of the peatlands (Figure 2-7). The water table regimes and characteristic plant communities will vary between microhabitats. These microhabitats will be affected by larger scale hydrological functioning from the whole peatland and the idea of understanding the nature of the linkage would help in the understanding of the hydrological behaviour of the peatland (Belyea and Baird, 2006). Hydrological metrics (e.g. water table depth) can be an effective predictor of the movement of carbon within the peatland system linking hydrology to the ecological and biogeochemical processes of the peatland ecosystem (Yu, 2006; Beer and Blodau, 2007; Wu *et al.*, 2011; Waddington *et al.*, 2015). This understanding of peatland carbon dynamics is important as it can then be scaled up to global change studies.

The internal (within peatland) hydrological feedbacks in northern peatlands were conceptually modelled by Waddington and colleagues in 2015 with a recognition that apparent interaction routes exist between disciplines (ecology, biogeochemistry, micro-meteorology). The model output was a flow chart that had alternating arrows to indicate feedbacks within peatlands and was created to further understand the resistance, resilience and vulnerability of peatlands to climate change. It was concluded that the model could include wider feedback loops to ultimately enhance the understanding of peatland ecosystems. This model focused on hydrological feedback loops centred on water table depths but this could be expanded further to include peatland ecology and biogeochemical relationships. The challenges associated with this include the number of interacting processes and feedbacks alongside the strength of the feedback which differs between peatland types (Table 2-1), among functions and across time (Waddington *et al.*, 2015).

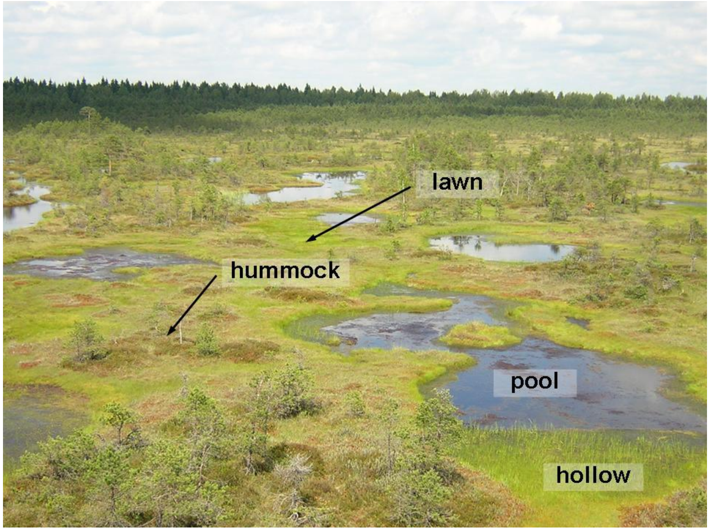


Figure 2-7: Peatland microhabitat landscape in Estonia

Although the diagram is of Estonia, the peatland microhabitat is also seen in the British Isles. The surface microtopography supports an array of birds, invertebrates and mammals through the provision of small-scale environmental conditions. Climate and slope determine the intricacy of the surface microtopography. An undulating bog surface is created by *Sphagnum* mosses which can grow in hummocks, low-growing lawns or in hollows. Surplus water is stored in hollows and pools and mossy ridges and hummocks will form during dry phases. Source: Kettridge (date unknown).

2.3.4 Regulating rainwater runoff

2.3.4.1 How peatlands respond to storms

As previously mentioned in Section 1.1.3, the uplands cover two thirds of Scotland's land. It is important to understand how the water moves from the top of the catchment down to where it is stored in the valley bottoms and how the condition of the peatland habitat can influence water movement and the impact on humans. Catchments of 5-10 km^2 in the UK can experience flash flooding, the flash floods peak in less than three hours and are a leading cause of risk to human life (Georgakakos and Hudlow, 1984). Peatlands are reported to regulate runoff by helping to retain the water thereby reducing the risk of flooding in downstream areas as well as improving water quality by acting as a filtering system reducing the turbidity and capturing the suspended sediment (House *et al.*, 2010). However, this statement might generalise a more complex topic than first thought. The perception of peatlands as a sponge (Turner, 1757) may indeed be misplaced. Peat is 90 % water but this water is often locked away, restricting its ability to store and absorb additional water (Ballard *et al.*, 2012). The result of this is a water table that is often within tens of centimetres from the surface resulting in a flashy runoff regime from the upland peatland habitat (Evans *et al.*, 1999; Holden and Burt, 2002a).

The hydrographs from eroded catchments have a shorter response time and higher peak flows when compared to the retention of water provided from an un-eroded catchment providing a smoother, wider shaped and smaller peaked storm hydrographs in comparison (Conway and Millar, 1960; Grayson *et al.*, 2010). Whilst searching the published literature it proved challenging to locate a comparison hydrograph to display the differences from eroded and un-eroded catchments. This was searched for to demonstrate any differences or similarities between comparable catchments monitored from an un-eroded and eroded catchment. This may represent an area for further investigation during restoration studies for the same location over time. The research study could look at hydrograph responses over time and monitor the change with reference to catchment conditions and land management prescriptions. The study by Grayson and colleagues in 2010 summarised the importance of vegetative cover in the response of the blanket bog to rainfall events. This is further supported by a rainfall simulation experiment carried out by Holden and Burt (Figure 2-8).

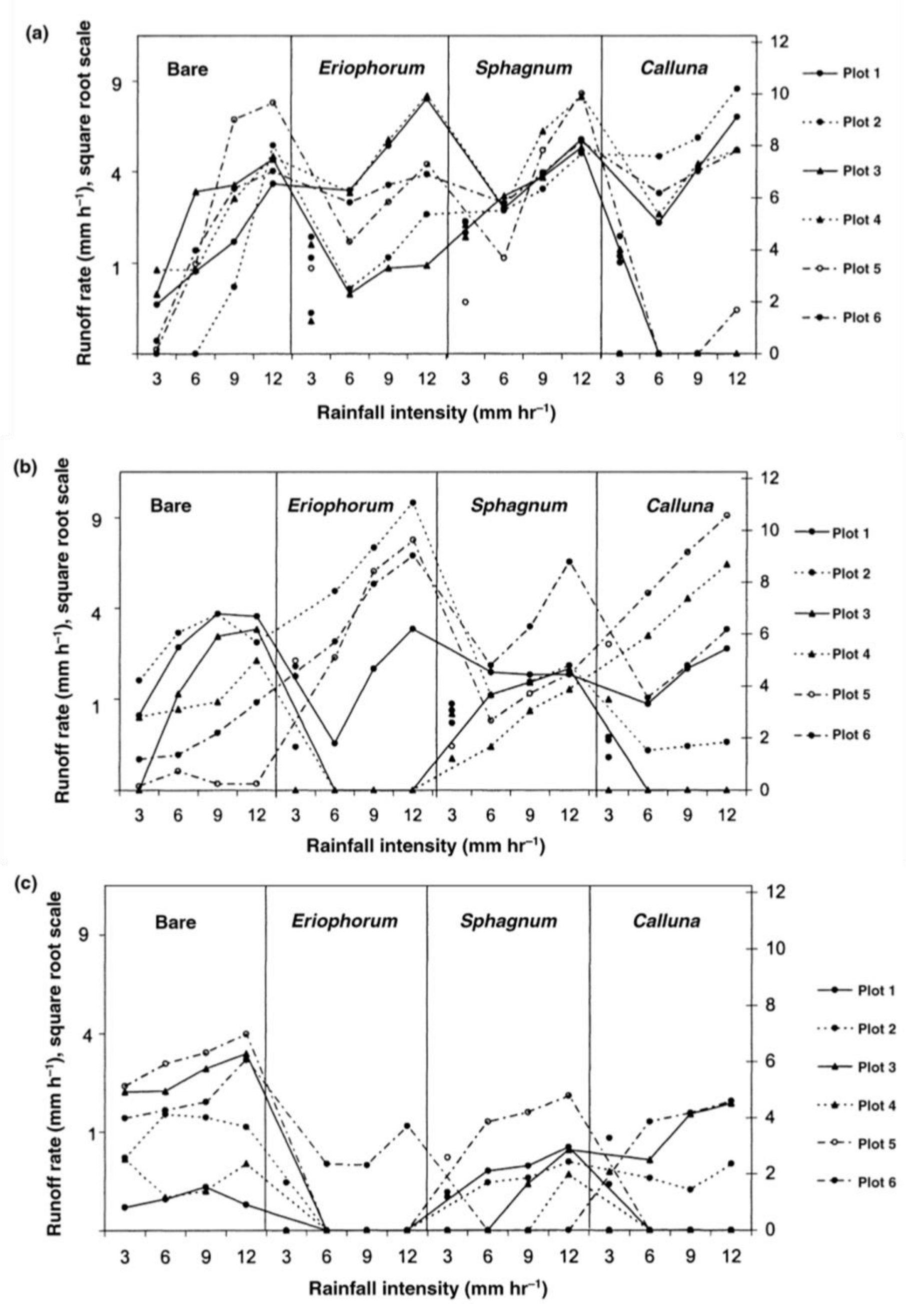


Figure 2-8: Steady state runoff rates by vegetation type with rainfall intensity

For; surface runoff (a), runoff at 5 cm depth (b) and runoff at 10 cm depth (c) (Holden and Burt, 2003a). Of the six datasets, the rainfall simulation experiment confirmed the dominance of overland flow on bare and vegetated peat surfaces. Overall, runoff production decreases with depth however variability in runoff with depth highlights that water movement within the peat is greatly variable. *Sphagnum* cover may release overland flow more slowly and vegetation cover had some influence (P = 0.06), however the properties of the peat structure below may be of more influence and are indicated by the surface vegetative cover. Source: Holden and Burt (2003a).

2.3.4.2 Seasonal influence on blanket bogs

Seasonal water deficits are more commonly experienced during the summer months resulting in water table drawdown and desiccation of peatlands. This can cause disturbances such as wildfires and droughts (Table 1-1). Other generalised seasonal influences that can impact on peatland hydrology include the spring growing season, autumnal flooding and winter snow cover.

Holden and Burt (2002) found that season can influence the precipitation-runoff response in blanket bogs. For instance, at a shallow depth, after a period of warm, dry weather the precipitation was found to infiltrate more easily into the blanket bog. This reduced the steady-state surface runoff rates as a result of more flow taking place within the peat. The remoteness of many upland blanket bog catchments and the technicalities of obtaining data on peat hydrology have proved challenging in studying and researching such environments (Evans *et al.*, 1999). Evidence must be balanced in relation to factors such as the topographic location, storage capacity and modification of the upland peatland habitat as all these factors can all have an influence on peatland hydrology.

2.3.4.3 Water flow pathways in peatlands

As mentioned in Section 2.3.4.1, a large amount of water is held within peatlands. However, only a small amount of rainfall would successfully manage to filter through. Flows of water include precipitation, evaporation, infiltration, throughflow, ablation and groundwater. The pathway and processes of water movement can differ depending on peatland condition. The water flow pathways differ between intact and degraded peat (Daniels *et al.*, 2008) (Figure 2-9). In studies relating to runoff in intact blanket bog, water table elevations are within the upper 50 mm of the peat surface where stream flow is mostly produced. Therefore, the majority of flow is generated from rapid saturation and infiltration excess overland flow generation (Evans *et al.*, 1999; Holden and Burt, 2002a; b, 2003b). Conversely, overland flow is significantly reduced in drained areas with macropore flow and pipeflow more important than in intact blanket bog (Holden *et al.*, 2006). A question arising from this in relation to this study site (the Mòine Mhór) is whether it behaves like a drained area or not? This will be explored further in Chapter 6.

A feature of a degraded peatland would include an eroding gully, which provides drainage, in turn lowering the height of the water table (Tallis, 1997). Gully erosion can increase the hydrological connectivity of the system through enhanced macropore flow produced by structural changes to the peat (Daniels *et al.*, 2008).

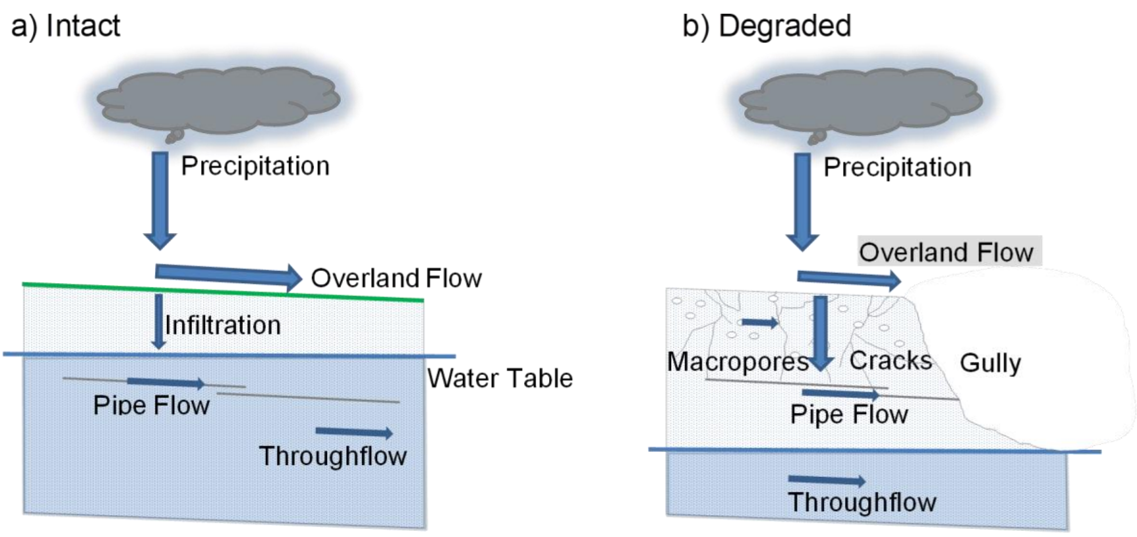


Figure 2-9: Water pathways in an intact (a) and degraded peatland (b)

The high water content of peat means that the water storage capacity is largely full therefore only a small amount of the precipitation falling on the surface is retained within the peat (in both a and b). In a healthy (intact) peatland the water table is close to the surface (a) for most of the year which is important for plant occurrence and growth thus enabling peat accumulation. Erosional gullying (stream channels) leads to lower water tables (b), increased rain runoff and increased erosion negatively impacting stream flow and water quality. Water tables in intact peatland system rise rapidly in response to precipitation. In the degraded system a rapid wet-up response is followed immediately by rapid draw-down after the event. More pronounced and larger in size in comparison to intact peat, macropores and/or pipes deliver water to the stream channels. In both systems groundwater input is minimal. Overland flow is dominant in the intact peatland (a) whereas the macropore flow network (b) is observed as more dominant in the degraded peatland (b). Inspired from; Daniels *et al.,* (2008).

2.3.5 Challenges in gathering upland hydrological data

The challenges in gathering upland data have been highlighted by Whitfield and colleagues who suggest that more research should be carried out in cold season processes (snow, frozen-peat and permafrost) to determine the impact of these cold processes on the hydrology of peatlands. With reference to Canadian peatlands, they suggest that headway with the cold season research will aid in predicting water yield on ungauged peatland-dominated watersheds (Whitfield *et al.*, 2009).

Despite the abundance of research already carried out in relation to peatland hydrology, uncertainties still remain such as how much carbon is lost through streams and other atmospheric movements. Ongoing research is addressing these remaining and unanswered questions, through mechanisms such as the development of technology, fieldwork, hydrological modelling and transdisciplinary working. Examples of developments include the publicly accessible carbon calculator tools to assess the impact of Scottish windfarm development on peatlands (The Scottish Government, 2018). Further afield, the SPRUCE experiment is currently being carried out within a *Sphagnum spp.* bog forest in northern Minnesota. The experiment aims to assess the response of northern peatland ecosystems to increases in temperature and exposures to elevated atmospheric carbon dioxide (CO_2) concentrations under predicted future climate scenarios (UT-Battelle for the Department of Energy, 2018). The multi-year continuous experiment operation (2015-2025) includes five temperature treatments duplicated across 10 enclosures (UT-Battelle for the Department of Energy, 2018). Furthermore, with the increasing availability and accessibility of data, satellite and remote sensing data has been used to identify potential areas for peatlands resulting in the discovery of previously unknown information on the distribution and magnitude of tropical peatlands such as those studied in the Congo (De Grandi *et al.*, 2000; Mayaux *et al.*, 2002; Dargie *et al.*, 2017).

Models are also increasingly using these data sources such as carbon emission models which are based on remote sensing data (Hamada *et al.*, 2016). Another developing area is the use of unmanned aerial vehicles (drones) to capture high spatial resolution images. The benefits of drones include covering a larger area than on the ground monitoring techniques could manage and the ability to capture centimetre resolution imagery and topographical data at a relatively low cost.

2.4 Peatland ecology

There is a close link between the hydrology and ecology of peatlands. Ecology can be described as the relationship between flora and fauna within the environment. Peatland ecology, described as a habitat and community of conservation value, is influenced by geographical location, local topography and altitude. Specialised plant biodiversity exists in the upland peat bogs.

2.4.1 Peatland vegetation

Peatland vegetation species including *Sphagnum* (peat moss), sedges (cotton grass and deer sedge) and heathers are common flora that have adapted to the highly acidic, low nutrient and waterlogged environment of the peat bogs (Scottish Wildlife Trust, 1997). The sundew and butterwort are carnivorous plants that trap insects to gain nutrients which are lacking from the acidic peat, particularly nitrogen (Figure 2-10) (Scottish Wildlife Trust, 1997).

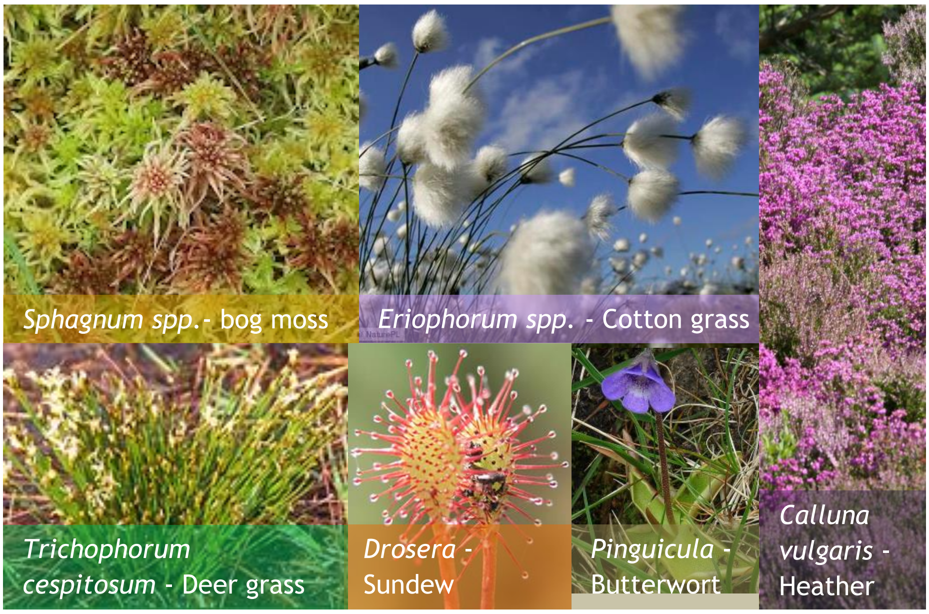


Figure 2-10: Common bog vegetation

The peat bog provides a unique home for a variety of plant species such as those highlighted above. Each are adapted and suited to the cool wet conditions in which they form. *Sphagnum* is the primary bog forming species. Cotton grass is well adapted to the boggy conditions and like deer sedge; it is a member of the sedge family. Drier hummocks of heather can be found in among the wet peatland habitat. Sundew and butterwort are carnivorous plants; this provides them with the nutrients they require in an acidic and waterlogged environment that is leached of many nutrients. Source of images: Stewart (2012); BBC (2013); NIEA (2010); Nature Gift Store (2013) and Darlington (2013).

2.4.1.1 *Sphagnum* moss

Sphagnum rich bogs are preferable for conservation and regeneration of peat bogs. *Sphagnum* is the powerhouse and ecosystem engineer which facilitates the growth of the bog. Large quantities of water can be stored inside the cells, larger plants grow on top of the *Sphagnum* moss and microscopic plant and animal life can be found within the *Sphagnum* providing food for the other organisms living in the bog. Once dead, the *Sphagnum* decomposes under the living surface and slowly forms into peat, delivering improved water quality and increased carbon storage benefits (van Breemen, 1995; House *et al.*, 2010). Living *Sphagnum* can absorb greater than eight times its weight in water, growing as a multi-coloured mat of many individual species which support each other (Scottish Natural Heritage, 2001). *Sphagnum* is perfectly adapted in its morphology, anatomy, physiology and composition for western and northern Scotland where rainfall, mist and fog are frequent, flushing and leaching out soluble nutrients in the soil leaving behind waterlogged and infertile soil (van Breemen, 1995). Different plant species, such as *Sphagnum* directly affect the uptake, use and loss of nutrients, which will have an indirect effect on microbial activity and herbivory (Hobbie, 1992).

2.4.1.2 Nutrients

The relationship between nutrient levels (trophic condition) and peatland vegetation has been recognised since the 1900's (Botch and Masing, 1983; Zoltai and Johnson, 1987). Nutrients from leachates and plant litter are largely input into peatlands by wet and dry atmospheric deposition which is efficiently intercepted by *Sphagnum* and other mosses which have high nutrient retention (van Breemen, 1995). In undamaged peatlands, nitrogen levels are tightly cycled. Elevated nitrogen input leads to losses in runoff of nitrate and ammonium but also as gaseous nitrous oxide (N_2O) and nitric oxide (NO) (Lamers *et al.*, 2000). Increasing atmospheric nitrogen decomposition can shift the vegetation community (decline in bryophyte species), in favour of species adapted to higher nutrient levels such as vascular plants, which results in a loss of diversity (Bobbink *et al.*, 1998; Bubier *et al.*, 2007). Studies support the inverse relationship between levels of nitrogen deposition and species richness (Dupre *et al.*, 2010; Maskell *et al.*, 2010; Tipping *et al.*, 2013).

Alongside nitrogen, phosphorous and potassium can limit productivity in *Sphagnum* peat bogs (Malmer and Wallén, 2005). In the southern Pennines in England, a combination of factors, including sulphur and high nitrogen pollution have damaged the peatland, putting the degraded peatland at risk of turning into grassland or scrubland (Evans *et al.*, 2006; Dise, 2009). Peatland acidity is the result of microbial decay, cation exchange and the addition of acids from the atmosphere (Priest, 2012). Microbial decay releases complex humic acid substances which are organic compounds resulting from the breakdown of dead plants and animal material by bacteria and fungi (Thurman and Malcolm, 1981, 1983). Cation exchange is the adsorption of base cations (Ca^{2+} and Mg^{2+}) and release of hydrogen (H^+) ions by *Sphagnum* mosses acidifying the peatland environment (Clymo, 1963). The addition of acids from the atmosphere into the peat depends on the net change in balance of cations and anions in precipitation as it passes through the soil profile (Gorham, 1984). The movement and concentration of nutrients available can influence the plant growth and vegetation composition in peatlands.

2.5 Interactions between peatland hydrology and ecology

2.5.1 *Sphagnum* and water table

As *Sphagnum* spreads out and covers the peatland, it increases the acidity of the soil through the release of hydrogen ions, further specialising its own environment by outcompeting other plants (Priest, 2012). The hydrological condition on peat bogs principally establishes the structure of the vegetation, and the extent of decomposition is determined by oxygen availability (Schellekens and Buurman, 2011). The depth and fluctuation of the water table controls these processes (Schellekens and Buurman, 2011). Significant seasonal events of interest to the increase in peatland water level include spring thaw, autumn rain and storm events.

2.5.2 Freeze-thaw cycle in peatlands

The temperature changes associated with freeze-thaw cycles and the resulting frost-heave particle detachment affect soil physiochemical and microbial activities (Wang *et al.*, 2014). The high latent heat content of water and the change of state from water to ice reflects the freeze-thaw process (Hromadka *et al.*, 1981; McKenzie *et al.*, 2007; Smerdon and Mendoza, 2010). The phase change is dependent on the physical properties and moisture content of the soil (Stähli and Stadler, 1997). The processes of subsurface seasonal freezing have been studied with a particular focus on permafrost regions (Woo and Winter, 1993; Osterkamp and Burn, 2003; Waddington *et al.*, 2015). Climate processes that affect the stability of soil properties include precipitation (wetting), evaporation (drying), freezing and thawing (Bullock *et al.*, 1988; Lehrsch, 1998).

The heat flux away from the freezing front and the water supply from the unfrozen soil are the main factors affecting the frost penetration within the soil (Edwards and Cresser, 1992). The rate and depth of freezing and thawing is party determined by the amount of insulation offered by the vegetation and snow cover (Edwards and Cresser, 1992). Frost penetration has been found to be inversely linked to the amount of litter and the degree of insulation it offers (Post and Dreibelbis, 1942; Harris, 1972).

2.5.3 Hydroperiod regime

The formation of niches for different plant species is in part controlled by the hydroperiod defined as the period in which a soil area is waterlogged (Foti *et al.*, 2012). The complexity of this ecosystem and the heterogeneous hydrological regime is acknowledged by Foti and colleagues (2012). In Southern New Hampshire (USA) a total of 103 wetlands were sampled and categorised into three hydroperiods based on the drying patterns observed in the field. This study highlighted that legislative protection should not focus on area (size) of the wetland alone but that assessment of hydroperiods should play a role in the protection of wetland amphibians (Babbitt, 2005). The hydroperiod regime results from the interplay between inflow, outflow and storage capacity of the peatland. Site conditions such as geology, soil, groundwater level, topography and vegetation composition influence storage capacity (Welsch *et al.*, 1995).

2.5.4 Peatland palaeohydrology

Blanket bogs are archives of archaeological and palaeoecological material. Palaeoecology assessments indicate that few, if any vegetation types in Western Europe are natural (Birks, 1996). Natural refers to areas that have not been modified by human activities and is thus a relative term in Western Europe today (Anderson, 1991; Gotmark, 1992). Of conservation value is the 25 % of Western Europe supporting semi-natural vegetation (Ratcliffe, 1986), where there is a dominance of confirmed native species and structure of presumed natural vegetation (Ratcliffe, 1977a).

Barber and colleagues (2003) established that plant macrofossils in ombrotrophic mires displayed good links between past vegetation composition and local hydrology. Past vegetation composition and changing palaeohydrological conditions are evident in peat humification (Barber *et al.*, 2003). Yeloff and Mauquoy (2006) put forward the idea that the vegetation composition has to be comparably homogeneous throughout the peat profile for climate to have a major influence on humification, but this is not always the case. They conclude that species-specific measures of humification and the influence of the surface wetness of the bog, and therefore climate, on peat humification should be examined (Yeloff and Mauquoy, 2006). The predominant vegetation in a peatland can impact on photosynthetic and respiration rates as well as the quantity of carbon available for mobilisation as DOC (Turner *et al.*, 2013). Baseline data collected from palaeoecological studies about the past ecosystem composition and function can help guide future ecosystem restoration and enhancement (Birks, 1996).

2.5.5 Micro-relief features within peatlands

The structure of blanket bogs is impacted by the surface vegetation (Holden, 2009). The living plant roots and litter have contact with the upper peat layer which can influence the structure and hydrological pathways (Holden, 2009). Effective porosity was found to be significantly affected by vegetation cover type (Holden, 2009). Indeed, *Sphagnum* plants are rootless so cannot endure erosive surface runoff (Bragg and Tallis, 2001). An intact bog commonly has an uneven surface displaying micro-relief with convex (hummocks, ridges) and concave (hollows, furrows, pools) features (Figure 2-11) (Bragg and Tallis, 2001). Physical processes can influence the structure of the peat (Holden, 2009). If the peat is bare, there is a risk of desiccation and frost-heave during dry and cold periods respectively (Holden, 2009).

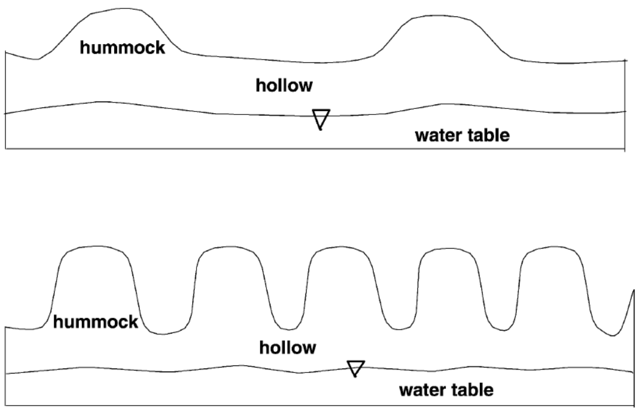


Figure 2-11: The difference between a hummock and a hollow

A hummock is a low mound rising from the surface of the bog and a hollow is a low flat area (Nungesser, 2003). Hummocks can be made of drier vegetation such as heather, blaeberry and crowberry with *Sphagnum* and peaty pools dominating in the flat areas. Widely spaced (top) and closely grouped together (bottom) hummocks are shown to display the variety of micro-morphologies present in bogs. Source: Nungesser (2003).

2.5.5.1 Geochemical study of peatlands

The geochemical study of past changes in atmospheric deposition is recognised as more suited to hummocks or lawns than hollows (Bindler, 2006). Malmer and Wallen (1999) found up to 1.6-fold differences in productivity and decay losses between lawns and hummocks when looking at lead ^{210}Pb as an indicator. The accumulation of lead was greater in the hummocks when compared to the lawns or hollows. The study also recognised that lichen hummocks and *Sphagnum* hummocks gave different results. In the lichen hummocks the mass balance was negative with higher productivity noted in the *Sphagnum* hummocks thereby maintaining the microtopography of the mire surface (Malmer and Wallen, 1999). These findings display how vegetation structure and composition can impact on the geochemical study of peatlands.

2.5.6 Zonation within peat bogs

Zonation of species and vegetation groups occurs within a small vertical range of between 0.5 – 0.75 m within peat bogs (Figure 2-12) (International Union for Conservation of Nature, 2014). The stability of the water table in peatlands, within 0.05 m of the surface allows for small zones (~10 m) of species to remain for centuries or millennia (International Union for Conservation of Nature, 2014).

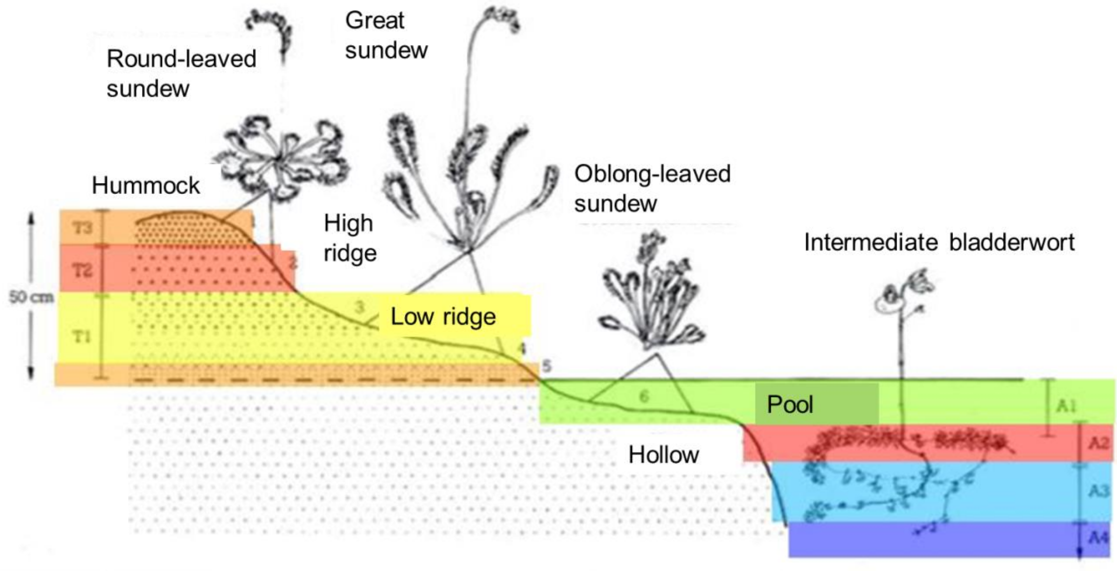


Figure 2-12: Small scale variability in species occupying peatland habitat

Note the various carnivorous species that utilise the hummock and high ridge area. Across the zones different *Sphagnum* species also dominate from the hummocks (1) to the ridges (6); *Sphagnum imbricatum* (1), *Sphagnum rubellum* (2), *Sphagnum magellanicum* (3), *Sphagnum papillosum* (4), *Sphagnum pulchrum* (5), and *Sphagnum cuspidatum* (6). Wildlife species such as the Dunlin also make use of these small zones e.g. nesting in the high areas and the feeding in the lower pools. Source: IUCN (2014).

2.5.7 Morphological classification

Peatland vegetation may be present in an area but not be the dominant vegetation. The key vegetation type within the area and the description of the habitat can dictate the type of morphological classification it receives. Five structural levels are assigned on a hierarchical scale of decreasing size to mires: macrotope, mesotope, mire margin/mire expanse gradient, microtope and microform (Joint Nature Conservation Committee, 2015). The morphological classification can sometimes miss that an area of blanket mire is comprised of topographical or hydrological mesotopes (Table 2-2) (Joint Nature Conservation Committee, 2015, 2017). Anomalies can exist within an area classified as a particular type; mixed types are therefore required in some places.

Table 2-2: Description of individual mire units (mesotopes)

Different morphological types of blanket bog resulting from their topographical position. Source: Joint Nature Conservation Committee (2015, 2017).

Blanket bog mesotopes	Description
Saddle mires	Occupies saddles between two or more summits
Watershed mires	Occurs on watershed plateaux or broad ridges, where the surrounding land slopes away on all sides
Valleyside mires	Occurs on gently sloping or almost level ground lying between higher, steeper terrain and a watercourse which forms its lower margin
Eccentric mires	Eccentric bogs slope mainly in one direction and occur on valleysides
Ladder fens	Characteristic surface patterning, with narrow pools and intervening low, narrow ridges parallel to the contours
Spur mire	Where the shoulder of a hill flattens into a broad spur, its crest often carries a lobe of blanket bog with a distinctive form

2.5.8 Ecological management of peatlands

The natural development of peatland ecology with reference to blanket bogs is dependent on favourable topographic and environmental conditions but humans can influence the peatland ecology composition through management (Page *et al.*, 2009). Changes in climate (precipitation, evapotranspiration) and land management (anthropogenic activity) can have an impact on vegetation patterns and species distribution in peatlands (Foti *et al.*, 2012). A reduction in the water table of only 20 mm is sufficient to prevent the growth of *Sphagnum* mosses (Ivanov, 1981). This may arise from a mixture of low intensity grazing and infrequent burning (Figure 2-13) (Bragg and Tallis, 2001). A high amount of grazing or burning is associated with the domination of graminoid vegetation (grasses). A lower amount of burning promotes a dominance of dwarf shrubs such as *Calluna vulgaris* (heather) and *Empetrum spp*. (an evergreen shrub that provides fruit) (Bragg and Tallis, 2001).

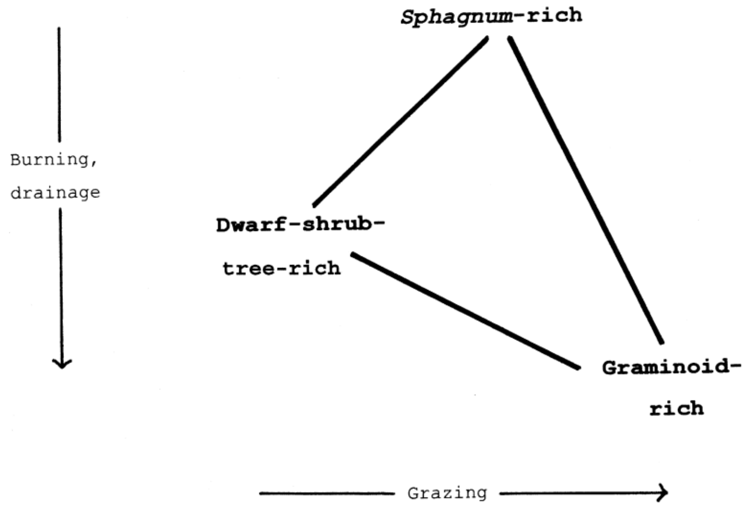


Figure 2-13: Generalised responses of blanket mire vegetation to grazing, burning and drainage

The response of mire vegetation to management (burning, drainage, grazing) is often complex as species can be more or less sensitive to the management impact. Low intensity grazing, infrequent burning and a lack of drainage typically favour an optimal *Sphagnum*-rich vegetative cover. At the other end of the spectrum, high grazing and/ or frequent burning typically results in graminoid (grass) rich species. Degradation can have significant global environmental and socio-economic impacts. Source: Bragg & Tallis (2001), p351.

2.6 Peatland function

2.6.1 Biogeochemical cycle

Peatlands are atmospheric sources of CO_2, methane (CH_4) and nitrous oxide (N_2O) making the biogeochemical processes important in relation to climate change, carbon sequestration and water quality (Ramesh-Reddy and DeLaune, 2008). The nitrogen and carbon cycle are strongly coupled and the consequence of enhanced anthropogenic nitrogen (N) deposition (eutrophication) on species composition, functions and sustainability of peat bogs is not fully understood (Sheppard *et al.*, 2013). *Sphagnum* is known to immobilise incoming nitrogen to the system although there is a limit to its effectiveness (Sheppard *et al.*, 2013).

2.6.2 Biological activity

Biogeochemistry is a multidisciplinary science that explores the physical, chemical, biological and geological controls on the environment within both natural and artificial ecosystems. Biogeochemistry, a sub discipline of biology and geochemistry includes consideration of the processes within and relating to the cycling of organic matter in the soil and water column (Figure 2-14). Techniques used to understand the population dynamics of soil organisms include new molecular, microscopic and analytical techniques. Plants can modify the soil physiochemical environment via rhizodeposition defined as the release of organic compounds into the surrounding environment (Nguyen, 2009; Trinder *et al.*, 2009). This process is influential ecologically as the loss of reduced carbon from the plant supplies an organic carbon pool to the soil microflora (Nguyen, 2009). The biological activity of soils e.g. nutrient and pollution cycling or the dynamics of soil borne pathogens is influenced by the soil microflora. It is important to understand the species of plant as this impacts on the secretion of carbon in turn influencing the microbial community which then feeds back on decomposition (Crow and Wieder, 2005). The direct (litter) and indirect (from the rhizosphere, the area of soil surrounding plant roots) controls on the rate and extent of decomposition are of significance in the turnover of terrestrial carbon (Trinder *et al.*, 2009).

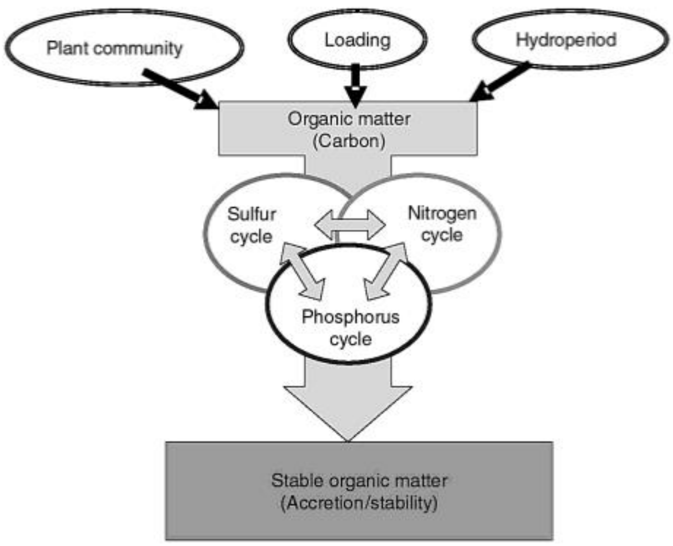


Figure 2-14: Biogeochemical cycling of organic matter in the soil and water column

Organic matter turnover is limited by the water logged conditions of the soil (hydroperiod). Nutrient loads can be stored long term in the organic matter (referred to above as accretion/stability). The plant community contributes the organic matter to the soil. Ecosystem functions are driven by biogeochemical processes in the soil. Peatlands provide long term nutrient stores (nitrogen, phosphorus, sulfur) in the soil organic matter. Nitrogen, phosphorus and sulfur are the primary components of soil organic matter and the cycling of these nutrients is coupled with carbon cycling. Source: Ramesh-Reddy & DeLaune (2008), p4.

2.6.3 Carbon cycle

The carbon cycle is the biogeochemical cycle by which carbon moves through the Earth's environment (geosphere / pedosphere, biosphere, hydrosphere, atmosphere). Carbon dioxide is removed from the atmosphere by marine phytoplankton and both terrestrial and aquatic plants in a process known as photosynthesis. Carbon dioxide is returned to the atmosphere by organisms, microorganisms and plants in a process known as cellular respiration (Campbell and Reece, 2005). Carbon is also passed from one organism to the next through the food chain forming the framework for the organic molecules fundamental to all organisms (Campbell and Reece, 2005). The sequestration of carbon is the proportion of inputs from plant matter against carbon loss, by natural biological conversion to CO_2 and CH_4 (Figure 2-15), hydrological carbon export and erosion (Ostle *et al.*, 2009). Degradation of peatlands by management and erosion can increase emissions of CO_2 and CH_4 (Lindsay, 2010). In terms of damaging gaseous emissions, the global warming potential of CH_4 is 34 times greater when compared with CO_2 over a 100 year period (Intergovernmental Panel on Climate Change, 2013).

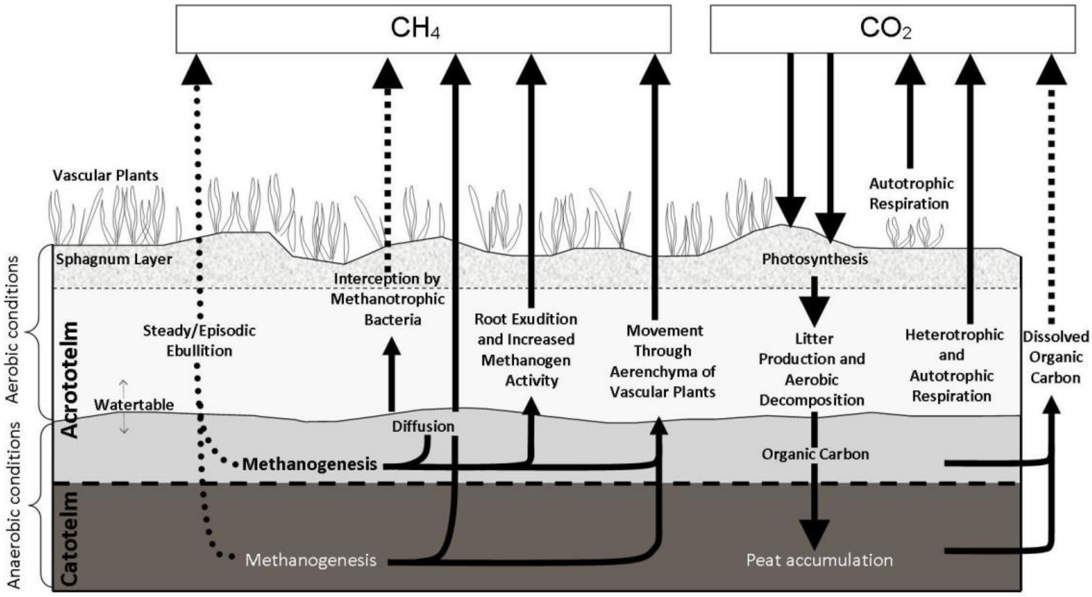


Figure 2-15: Surface exchange of carbon dioxide and methane in a peatland system

The natural fluxes are connected with the physical conditions and vegetation composition of the peatland system (Taylor, 2014). The pathways of the atmospheric release of CO_2 and CH_4 are shown above. CH_4 is generated by the breakdown of organic matter in the anaerobic layer by microorganisms. The aerobic layer is where the CH_4 is oxidised by methanotrophic bacteria. The loss of CH_4 can also occur via a more direct route from the anaerobic layer to the atmosphere. The equilibrium between primary productivity (influenced by vegetation and peatland type) and ecosystem respiration (influenced by height of water table and soil temperature) can impact on the sink or source status of the peatland. Peatlands sequester CO_2 resulting in stores of soil carbon within the peat. Hydrological losses of carbon include dissolved organic carbon (as well as inorganic carbon and particulate organic carbon). Organisms that are heterotrophs use organic carbon for growth and autotrophs fix carbon from inorganic substances to produce organic substances. Source: Taylor (2014), p24.

2.6.4 Carbon storage

Peatlands hold around 20-30 % of the world's total soil carbon storage (Gorham, 1991) and roughly 50 % of the UK's total soil carbon storage (Milne and Brown, 1997). The UK's peatlands (inclusive of upland blanket, lowland raised bogs and fen peats) contain 5.1 billion tonnes of carbon, with the bulk located in Scotland (4.5 billion tonnes) (Figure 2-16) (Smith *et al.*, 2007a; b).

Inputs by photosynthesis are generally greater than the losses from decomposition, resulting in an accumulation of carbon in peatlands (Andersen *et al.*, 2013). However, catastrophic losses can result in a mass loss of carbon such as from the 100,000 plus ha of peatland forests which are destroyed each year for palm oil and agricultural plantations emitting thousands of years of carbon accumulation (Gaveau *et al.*, 2014). Over a period of seven days, 10 % of Indonesia's total annual emission was released as a result of one wildfire event in 2012 releasing 1.5-2 billion tonnes of carbon (Gaveau *et al.*, 2014). More locally, within the British Isles, bog bursts have resulted in a mass loss of carbon (Bowes, 1960; Tomlinson, 1982; Carling, 1986; Warburton *et al.*, 2003; Caseldine and Gearey, 2005). Globally, boreal and subarctic peatlands store an estimated total of between 270 and 370 petagrams of carbon (1 Pg = 10^{15} g) (Turunen *et al.*, 2002).

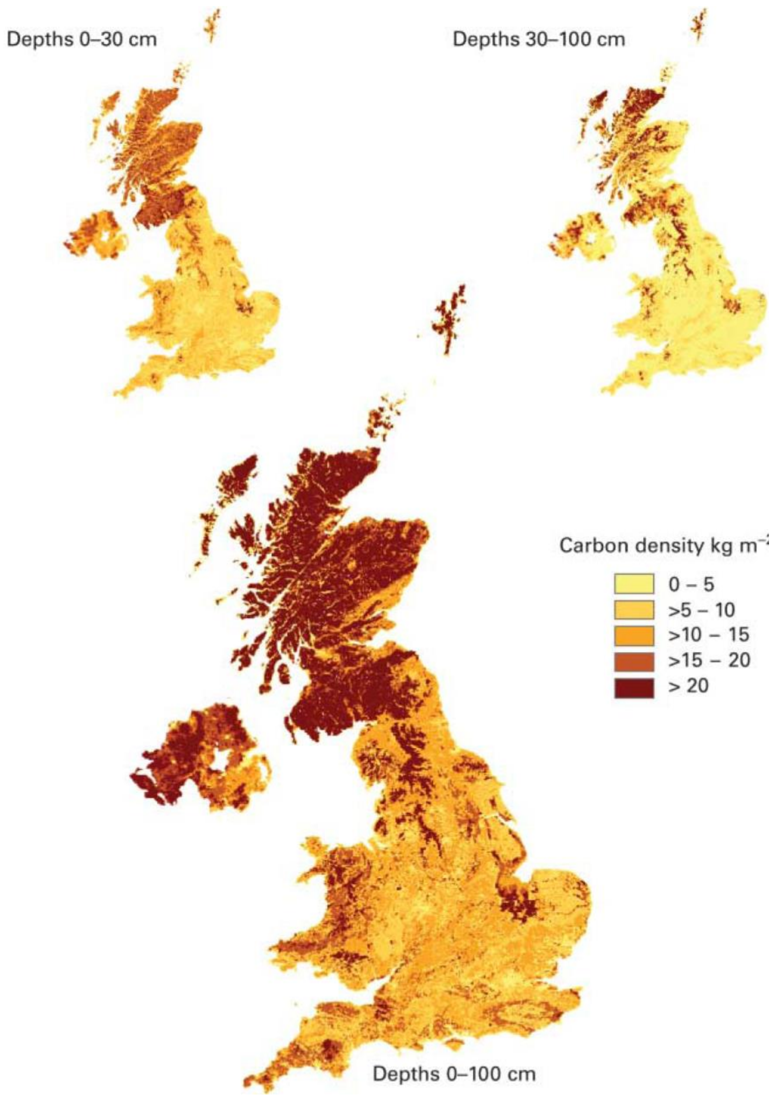


Figure 2-16: UK soil carbon map with carbon density in kg m^{-2}

Data was collected on soil type and land use to estimate soil carbon stocks on a 1 km grid across the UK (Bradley *et al.*, 2005). The total stock of soil carbon for depths of 0-100 cm is shown and is further broken down to 0-30 cm and 30-100 cm. Scotland is predominately under semi natural conditions and has a higher density of peaty and deeper soils in comparison with the rest of the UK. Source: Bradley *et al.,* (2005).

2.6.4.1 Carbon source

Increased soil decomposition and reduced vegetation productivity results in the release of atmospheric CO_2 (Lucchese *et al.*, 2010). High and stable water levels allow the gradual decay of plant matter and carbon transfer to storage to the catotelm (Lucchese *et al.*, 2010). The delicate balance can be disrupted and the peatland can switch to a carbon source, thus releasing its stored carbon to the atmosphere. This occurs if the acrotelm is breached, lowering the water table and leaving the catotelm susceptible to aerobic microbial degradation (Parkyn *et al.*, 1997). The atmospheric gaseous exchanges of carbon from peatlands include CO_2 and CH_4 as part of plant soil organism decomposition (Worrall *et al.*, 2003a). Changes in temperature and hydrology can affect the decomposition rate of peat. A rise in temperature increases microbial activity and decomposition of the peat resulting in higher CO_2 emission rates (Silvola *et al.*, 1996a; Bubier *et al.*, 1998).

2.6.5 Carbon fluxes and hydrology

The temporal and spatial variability of peatlands is large but understanding can be enhanced through the assessment of environmental and ecological variables (Blodau, 2002). Peatlands can be both carbon sinks and sources and the movement of water in peat is what drives carbon storage and flux (Blodau, 2002; Lal, 2004; Holden, 2005d; Maltby and Barker, 2009; Bispo *et al.*, 2016). Therefore, hydrology is fundamental to peatland development or decay (Holden, 2005d). The interaction of vegetation, decay processes and hydrology underpins peatland development and carbon accumulation (Holden, 2005d). The water table depth (determines the extent of the anaerobic and aerobic layers) has been found to correlate with CH_4 fluxes highlighting the importance of the hydrology of the peatland system in influencing fluxes (Moore and Knowles, 1990; Funk *et al.*, 1994; Shannon and White, 1996).

2.6.6 Fluvial carbon export

2.6.6.1 Carbon pathways

The primary quantity of carbon entering a stream is controlled by hydrological pathways (Dawson *et al.*, 2001). The fluvial flux of carbon from peatland includes: dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), particulate organic carbon (POC) and dissolved CO_2 (Figure 2-17) (Worrall *et al.*, 2003a). The high rates of aquatic loss of carbon from peatlands can take place over a brief period of time, which can be triggered by heavy rain or snowmelt, resulting in high flow and a loss of DIC, DOC and POC. Particulate carbon is the main part of fluvial carbon loss from eroding mires (Evans *et al.*, 2006). The DIC is carbon from carbonate sources. The DOC and POC contain the colloidal and suspended forms of carbon (Worrall *et al.*, 2003a). The definitions relate to the size fraction of the organic carbon where colloidal and suspended forms are finely divided particulate matter and the remaining fraction is truly dissolved (Riise *et al.*, 2000; Pokrovsky *et al.*, 2010). The dissolved CO_2 can come from organic and inorganic sources and is the CO_2 dissolved in the stream water above and beyond that which could be anticipated from equilibrium with the atmosphere.

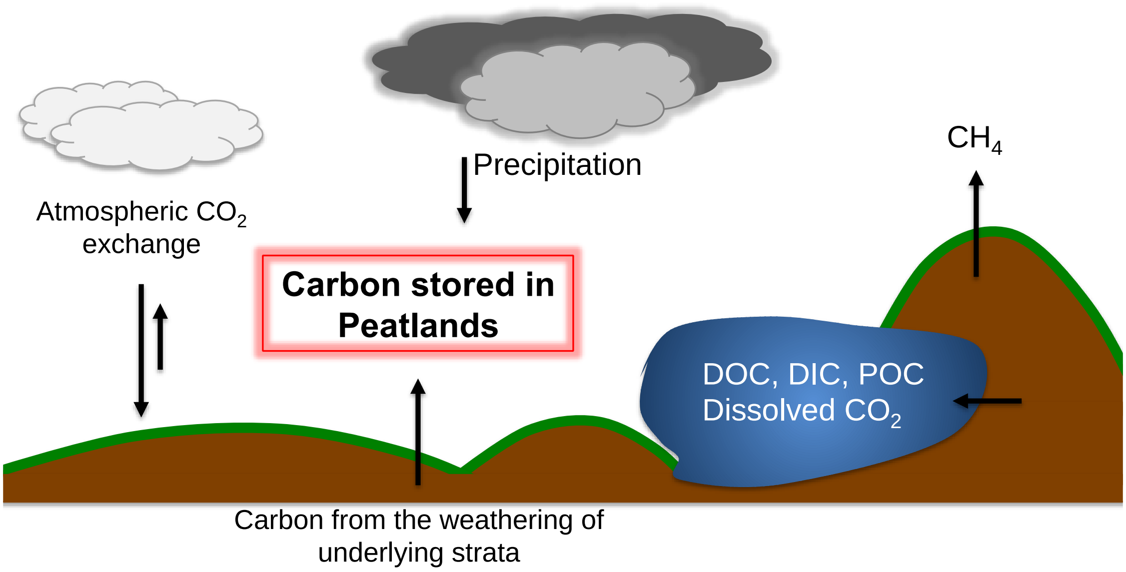


Figure 2-17: Carbon uptake and release pathways for upland peat

Atmospheric gaseous losses include carbon dioxide (CO_2) and methane (CH_4). If the peatland is functioning optimally it will sequester CO_2. Fluvial losses include dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC) and dissolved CO_2. Own drawing and inspired from Worrall *et al.,* (2003).

Microbial biotic and abiotic respiration processes within streams can affect concentrations of DOC, DIC and free CO_2 (Hope *et al.*, 1994). Soil carbon content and percentage of peat cover were found to be of significance in the control of river carbon fluxes in small scale headwater catchments (Hope *et al.*, 1997; Dawson *et al.*, 2001). Although terrestrial organic carbon inputs (allochthonous origin) become less relevant as the stream size increases, this places a significance on organic transport from upstream and autochthonous primary production (Vannote *et al.*, 1980).

2.6.6.2 Dissolved organic carbon

Stream DOC is made up of an intricate pool of molecules along an oxidation continuum (Battin *et al.*, 1999). Within the streambed, DOC is immobilised by the extracellular polymeric substances (EPS) matrix and is thus available as energy and carbon to the heterotrophic biofilm microorganisms (McDowell, 1985; Fiebig and Lock, 1991). The EPS is made up of microorganisms which stick to each other and adhere to a surface creating biofilms. The chemical composition of stream DOC principally follows catchment and channel processes, with flow paths and seasonality dictating the contribution of DOC from allochthonous (*ex-situ*) and autochthonous (*in-situ*) sources.

The relationship between DOC sources and sediment biofilm functioning was explored in a study by Battin and colleagues in 1999 of Mediterranean and temperate streams in Spain and Austria, respectively. The study concluded, that in the temperate stream, frequent storm flows scoured the stream bed (channel processes), abrading the biofilm matrix, thereby preventing EPS from accumulating. As a consequence of these changeable inputs of terrigenous DOC (made of material eroded from the land), it was found that a low EPS along with elevated metabolism allows the bacteria biofilm to quickly respond and recover making them highly effective in immobilising and retaining DOC molecules (Battin *et al.*, 1999). By contrast, in the Mediterranean stream, the low summer flows with no physical disturbance (channel processes) allows the EPS to grow. In association, the input of terrigenous DOC remains low and decomposition pathways of soil organic matter (catchment scale processes) yield DOC with low availability to the bacteria biofilm. However, the autotrophic biomass is abundant (Romaní, 1997) providing a continual DOC release in the Mediterranean stream. The microbial biofilm community in both streams responded to catchment processes e.g. climate, vegetation and diagenesis (conversion to rock) of terrigenous DOC and channel processes e.g. storm frequency and scouring (Battin *et al.*, 1999).

2.6.6.3 In-stream processes

In UK upland stream catchments around 10-30 % of the total carbon flux is exported as CO_2 (Neal and Hill, 1994) influenced by biotic instream processes (e.g. photosynthesis, respiration and decomposition) (Hoffer-French and Herman, 1989; Rebsdorf *et al.*, 1991). The concentration of CO_2 in streams is dependent on a number of determinants; temperature, season, soil moisture, soil type, oxygen and nutrient availability, soil organic matter content, stream turbulence, velocity, depth and gradient (Rebsdorf *et al.*, 1991; Howard and Howard, 1993; Jones and Mulholland, 1998).

A study of a peaty upland headwater catchment in north east Scotland by Dawson and Billett (2001) suggests that instream processing of DOC, DIC and outgassing CO_2 are important controls on the spatial variability of carbon fluxes (Dawson *et al.*, 2001). In stream processing between the headwater tributaries and the final flux at the catchment outlet were estimated to remove 12-18 % of DOC, 43-1102 % of DIC and 369-996 % of outgassed CO_2 (Dawson *et al.*, 2001). Losses of DOC were attributable to biotic processes (biofilm respiration, adsorption onto algae) and abiotic uptake (adsorption onto mineral surfaces e.g. aluminium) (Davis, 1982; Thomas, 1997). However, it is noted that higher flows than those captured during sampling may have resulted in a gain in DOC production in the headwater tributaries as a result of the formation from fine POC. The loss of DIC was attributed to a net loss in bicarbonate (HCO_3) linked to increased biological activity downstream, reduced groundwater inputs and the CO_2 removed from the stream by outgassing (Dawson *et al.*, 2001). A split of approximately 40:20:20 for DOC:POC:DIC has been modelled for global fluvial carbon fluxes (Moody *et al.*, 2013).

To quantitatively assess the impact of light conditions on DOC loss, degradation measurements were carried out monthly over one year from four sites on the River Tees in northern England. The water samples collected were transferred and sealed into quartz glass tubes which allowed light to pass through. To prevent exposure to light, some of the replicate samples were wrapped in foil, resulting in the collection of light and dark samples. Exposure to light was monitored in the outdoor environment and degradation was measured over timescale relevant to river residence timescales, the estimated residence time of 12.9 to 127.2 hours was considered. The residence time represented the time taken for river water to transit from the point of entry to the point of monitoring and was calculated using information available from gauging stations within the River Tees catchment. Residence times in rivers generally range from hours to days. In comparison, the residence time from lakes would be months and is of relevance when considering the age of the DOC measured. The authors conclude that there is a strong influence of radiation on the loss of DOC (Moody *et al.*, 2013). With reference to permafrost soils, a study by Cory and colleagues in 2014 found that photochemical oxidation accounted for 70 to 95 % of the processed DOC in the water column of arctic lakes and rivers. The importance of photochemical processing of DOC in arctic freshwaters was emphasised which contributed around a third of the total CO_2 released from surface waters in the river basins studied (Cory *et al.*, 2014).

In peatland catchments, photo-processing is also known to be an influential process in the transformation of aquatic DOC with the photoactivity of DOC higher in the headwater streams (Pickard *et al.*, 2017). Around half of the carbon exported as DOC to freshwaters is lost to the atmosphere as CO_2 indicting the combined importance of microbial and photochemical pathways in the instream processing and export of carbon (Tranvik *et al.*, 2009; Cory *et al.*, 2014; Pickard *et al.*, 2017). As connectivity between DOC sources and streams is reduced, instream photodegradation and decomposition become more dominant (Tunaley *et al.*, 2018).

The production, mobility and instream processing of DOC concentration is driven by hydrological processes. The interplay between factors potentially driving DOC cycles was analysed by Tunaley and colleagues in 2018, based on high frequency measurements of discharge, specific conductivity, pH, groundwater levels, temperature, evapotranspiration and solar radiation at a peatland dominated first order stream in the Scottish Highlands (0.65 km^2) (Tunaley *et al.*, 2018). It was found that maximum stream water DOC concentration occurred with an afternoon flush from the riparian peat zone to the stream controlled by antecedent temperature. The complexity of these DOC cycles in northern catchments is important in understanding stream functioning and the global carbon cycle (Tunaley *et al.*, 2018).

2.6.7 Previous studies and trends in aquatic carbon

In UK upland catchments and other northern temperate areas many studies report an increase in DOC concentrations over time. However, the factors controlling the increases are not yet fully understood (Freeman *et al.*, 2001; Worrall *et al.*, 2003b, 2004a; Clark *et al.*, 2010a). Monthly DOC concentration datasets varying from 8 to 42 years in length were compiled by Worrall and colleagues from 198 catchments spread across the UK. A significant upward trend of DOC was found in 153 catchments (73 %) with the remaining showing no significant trend. The mean annual increase in DOC was 0.17 mg C/l/year (Worrall *et al.*, 2004a). The increase in DOC concentrations in the dataset was independent of regional effects such as rainfall, nitrogen deposition and land use change and resulted in discounting several explanatory factors potentially attributable for the increasing DOC concentrations. The study concluded that climate induced temperature changes and corresponding impacts of land use change and eutrophication may be responsible for increased DOC concentrations (Worrall *et al.*, 2004a). Further research by Worrall *et al.* reported that air temperature changes account for a 12 % increase in production rate of DOC and climate change for a 6 % increase in DOC flux. It was therefore hypothesised that an enzymic latch mechanism is an additional process responsible for increases in DOC production (Worrall *et al.*, 2004b). Increased DOC release could follow periods of water table drawdown or drought as enzymes are switched on by water table drawdown but are not switched off instantly after water table rise (Worrall *et al.*, 2004b). This response would cause increased peat decomposition and therefore increased DOC release.

Clark and colleagues recognised that many drivers have been proposed for increasing DOC trends. However, a universal agreement is that increases in DOC are likely to be detrimental to the environment (Clark *et al.*, 2010a). Recognition is made that multi scale temporal drivers are responsible for DOC concentration increases inclusive of regional acid deposition loading differences (Clark *et al.*, 2010a).

In a further study of the factors influencing the DOC dynamics in surface waters, Worrall and Burt utilised data from 208 rivers from 1975 to 2003 to calculate the DOC flux for Great Britain. The DOC flux peaked at 1.68 Mt C/yr, or an export of

6.6 tonnes C/km^2/yr (Worrall and Burt, 2007). This particular study highlighted that the changes in DOC flux are small compared to those found in DOC concentrations indicating that concentration trends do not directly compare to changes in carbon storages in soil. The study concluded that water throughput such as runoff and rainfall were the prevailing control in increasing DOC production (Worrall and Burt, 2007).

Utilising a two year dataset, Dinsmore *et al.* (2010) assessed the importance of aquatic fluxes to the sink/source strength of Auchencorth Moss by quantifying the loss of GHGs (CO_2, CH_4 and N_2O) and aquatic C (gaseous, particulate and dissolved). The findings from the Scottish peatland system concluded that is important to consider both the GHGs and aquatic C budgets, with the greatest fluxes in both noted to be net ecosystem exchange (Dinsmore *et al.*, 2010).

2.7 Peat erosion

The soil carbon stocks in peatlands can remain the same or be improved by stopping or reducing peat extraction, drainage, liming, nitrogen fertiliser use and grazing (Silvola *et al.*, 1996a; Waddington and Price, 2000; Haigh, 2006; Ward *et al.*, 2007). Land use on peatlands can have negative consequences resulting in the erosion of peatlands. Peatlands reflect the particular conditions in which they have developed, and vegetation change or erosion can affect these exceptionally sensitive landscapes (Bragg and Tallis, 2001). Actively growing UK blanket bogs can typically fixate 40-70 gC/m^2/yr (Worrall *et al.*, 2003a). The production and decomposition balance for the acrotelm must always be positive in order to preserve the existing depth of peat (Bragg and Tallis, 2001). If there is a decline in vegetation growth or cover or a lowering of the water table, the peat will experience degradation (Bragg and Tallis, 2001).

2.7.1 Degradation of peatlands

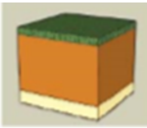
Erosion of peat varies spatially across locations from a few sparsely distributed rills, hags or gullies, to the more severe scenarios where there are extensive areas of bare and exposed peat with the surface vegetation entirely removed. The five categories that relate to the increasing severity of peatland degradation are: active, degraded, bare, archaic and wasted/lost (Table 2-3) (Lindsay and

Immirzi, 1996; Bruneau and Johnson, 2014). Active peatlands are likely to be peat forming due to a vegetative cover and generally unmodified hydrology. This is inclusive of previously degraded peatlands where management has favourably restored near-surface water levels. Providing the damaging activities have stopped and the system is given time, peatland regeneration is possible however the process happens faster with intervention (Lindsay *et al.*, 2016). Degraded peat has a semi-natural vegetative cover dominated either by graminoids (grasses) or ericoids (e.g. heather). Bare peat associated with activities such as peat cutting, overstocking or possibly from long-standing natural erosion is distinctive from the lack of vegetative cover whereby peat is lost through wind and water erosion pathways. Archaic peat has been affected by a significant change of land use (e.g. cultivation) but may still have a considerable depth of peat soil. Wasted peat is absent of peat-forming vegetation and most peat has been lost or removed often resulting in soil mineral material predominating.

To help quantify the carbon impacts, as part of the feasibility study for Peatland ACTION funding, information regarding the peatland condition is required. The peatland condition assessment assigns four categories to peatland condition: near-natural, modified, drained and actively eroding (Table 2-3) (Birnie *et al.*, 2017). Similarities are evident in the two categorisations in relation to the ecological conditions of the peatland categories outlined.

Table 2-3 Categories and key features associated with peat condition/degradation

Comparison between the five categories assigned by Lindsay and Immirzi in 1996 and the four categories identified in the Peatland Condition Assessment in 2017.

Lindsay and Immirzi (1996)		Peatland Condition Assessment (2017)	
Category	Key features	Category	Key features
Active 	Optimal state for long term carbon storage in catotelm	Near-natural 	*Sphagnum* dominated, natural pools may be present
Degraded 	Associated with burning, drainage, afforestation of peatland	Modified 	Bare peat in small patches, domination of heather or purple moor grass
Bare 	No vegetation, associated with peat cutting, wildfire, pollution, overstocking	Drained 	Within 30 cm of artifical drain (grip) or a revegetated hagg/gully system
Archaic 	Associated with cultivated land, forestry and deep drained	Actively Eroding 	Hagg/gully system, continuous peat surfaces, overgrazing
Wasted or Lost 	Most peat lost or removed – agricultural vegetation (grassland/cropland)		

2.7.2 Drivers of erosion

It is often challenging to establish what the initial and consequent drivers of erosion are (Aalders *et al.*, 2011). In blanket bogs, frost heave and desiccation are commonly cited mechanisms for the detachment of erodible materials which are then transported by wind, rain or runoff (Tallis, 1973; Francis, 1990). This then weakens the exposed surface layer of peat which is readily eroded, transported and removed from its location by wind, water or oxidation (Tallis, 1998). The process of blanket bog erosion can be caused by natural events or other events that can disrupt and remove the vegetative cover including: bog bursts, air pollution, fire, over grazing, peat cutting, artificial drainage and trampling (Yeloff and Mauquoy, 2006).

Sites at high altitudes are generally vulnerable to erosion even when animal densities are low (Cummins *et al.*, 2011). The erosion of peat can take place over wide areas and can lead to the loss of large amounts of peat material (Joint Nature Conservation Committee, 2011). The major processes concerned with peat erosion are water erosion (gullying, rilling and sheet erosion), mass movements (landslides) and wind erosion (Aalders *et al.*, 2011). Over the past 1000 years, between 5- 33 % of blanket bogs in the UK have been degraded as a result of gully erosion (Evans and Warburton, 2007). Peat can be eroded at up to rates of 5 cm per year from the entire surface or along lines of favoured water flow. These slowly cut in to the land to produce the gully systems that are typical of an eroding blanket bog (Tallis, 1998). A visible feature of peat erosion is the lack of vegetation resulting in a bare surface which can result in an increase in peat and mineral sediment loss from the site.

2.7.2.1 Aeolian erosion

Aeolian processes (relating to wind) are a relatively under-studied topic despite strong winds being characteristic of the UK upland environment (Foulds and Warburton, 2007). The knowledge of the processes responsible may be lacking but the potential of erosion by wind has been described for several decades (Bower, 1960; Radley, 1962; Tallis, 1965). The findings of a short study (two weeks) of peat desiccation (using mass flux sediment samplers and automatic weather station data) in the North Pennines reported that dry blow processes may become more significant in UK upland areas if climate change promotes more frequent surface desiccation. Ongoing desiccation can risk the switch from a *Sphagnum* bog dominated composition to a *Molinia* meadow (grassland formations) and later into a forest as displayed in the German peatland 'Dubringer Moor' (Lehmitz, 2014) (Figure 2-18). The erosion of peat soil by water or wind is a natural process but human practices are accelerating the process by removing particles faster than they can be formed hence leaving the surface bare and inhibited in its capacity to function optimally as a carbon store (Mortlock, 2007).

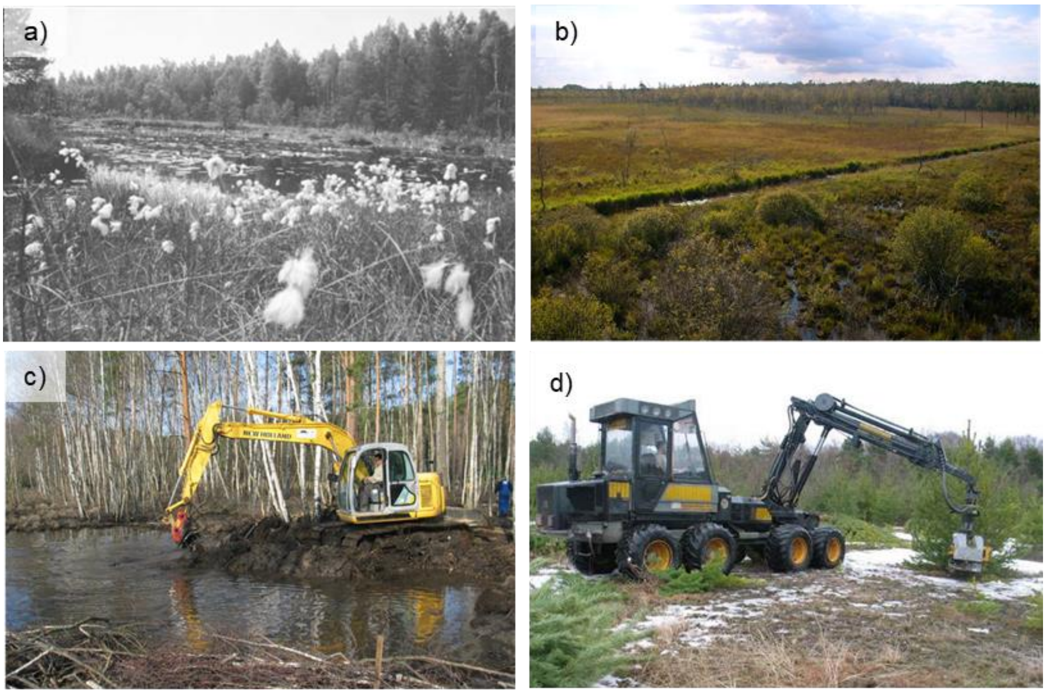


Figure 2-18: The Dubringer moor

The Natura 2000 Area is located in the north east of Saxony, Germany. The peatland has suffered from anthropogenic disturbance which has resulted in desiccation. The decline in *Sphagnum* species richness is apparent in photographs from 1984 (a) and 2012 (b). Restoration activities involving ditch blocking, restoring bog pools (c) and scrub clearance (d) are ongoing. Source: (Bastian and Steinhardt, 2002; SeptemberWoman, 2012; Wittichenau, 2016).

2.7.3 Anthropogenic influence on peat erosion

Peat erosion is variable but is essentially the result of a complex interaction between climatic, topographical and anthropogenic influences taking place over a prolonged period of time (Aalders *et al.*, 2011). Disturbances (climatic or land management) can alter the balance between the forces of erosion (frost-heave, desiccation, wind and runoff) against the capacity of the peatland to maintain a vegetative cover (Li, 2014). Anthropogenic activities that can influence blanket bog erosion include pollution, grazing, artificial drainage, accidental fire and prescribed burning (Willis *et al.*, 1982; Holden, 2005a).

A study at Featherbed Moss in the South Pennines, Northern England, found that the estimated total volume of peat lost from a gully (National Grid reference SK 0992, area size not specified) in one year was about 200-300 kg dry weight of peat (Tallis, 1973). This equated to a volume of 470 m^3 of erodible peat (Tallis, 1973). From the total volume of the gully it was calculated that the gully must have taken around 200 years to form and the cause of erosion was likely triggered by moor burning (Tallis, 1973). Anthropogenic disturbance may have caused the onset of erosion but the climate, topography, vegetation and water movement can influence the total volume of peat erosion thereafter. Erosion was found to be at its peak during the winter months notably when frost had broken up the surface of the peat and snowmelt then produced extreme water runoff (Tallis, 1973; Tallis and Switsur, 1973). High stream flow rates exceeding 40-50 l/min as a result of snowmelt or storms were found to be correlated with substantial peat erosion (Tallis and Switsur, 1973). Natural weather events can easily cause negative affects to bare peat as shown by Figure 2-19.

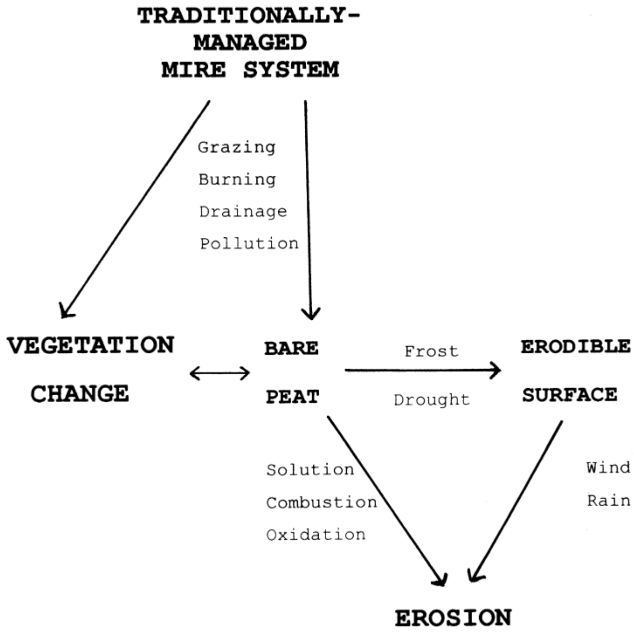


Figure 2-19: The roles of contributory factors to vegetation change and erosion in a sensitive blanket mire system

The traditional managed mire system has been subject to grazing, burning and drainage making it vulnerable to vegetation change and erosion. The removal of vegetation leaves the bare peat at further risk of being damaged by natural weather conditions resulting negatively on the mire system. Source: Bragg and Tallis (2001).

2.7.3.1 Grazing impacts on peatlands

Grazing of vegetation by domestic sheep in the UK uplands increased in the 1950s and 1960s. This was the result of subsidies available for improvements of hill grazing through artificial drainage. The 1970s and 1980s subsidies were linked to the EU Common Agricultural Policy (CAP) as subsidy payments, which have since been removed, as they actively encouraged higher stocking rates (Holden *et al.*, 2007a). Peatlands can only maintain low levels of seasonal grazing as a result of the low productivity of the vegetation (Joint Nature Conservation Committee, 2011).

Overgrazing modifies the peat vegetation with a reduction in dwarf shrubs where graminoids characteristically over grow or the peat surface is left bare. Compacted sheep tracks reduce the infiltration capacity, increasing the potential of overland flow carrying sediment and pollutants (Holden *et al.*, 2007a). Recovery of the system can realistically be achieved under optimum conditions within 5 years of the cessation of grazing (Cummins *et al.*, 2011). Recreational activities and trampling by humans can also cause a loss in carbon storage (Grieve, 2000). The land use history at sites is often complex and linking one particular pressure such as grazing (by sheep or wild deer) to peat erosion is challenging (Ellis and Tallis, 2001). The original trigger of blanket bog erosion may pre-date the onset of intense grazing but it still impacts negatively on the ecosystem.

2.7.3.2 Drainage and muirburn

Overall, drained peatlands are not seen as a significant determinant in the intensification of peat erosion in Scotland due to the observation of many eroded bogs that have no drainage channels (Cummins *et al.*, 2011). However, it is widely acknowledged that the restoration of drained peatlands is essential to restore the hydrological integrity and raise the water table in eroded peatlands.

The Muirburn Code which aims to prevent any future damage as a result of burning to upland blanket bogs came into force in Scotland in 2002 and was revised in 2011 (The Scottish Government, 2011). In brief, the current revision introduced changes relating to the season dates, licensing and neighbour notification. Despite the long use of fire, the relationship between fire, ecological condition, hydrological and recovery process in blanket bogs is still uncertain and remains poorly documented (Lindsay, 2009).

2.7.3.3 Acid deposition

Man-made acid deposition became a significant issue during the Industrial Revolution. The relationship between acid rain and atmospheric pollution was first discovered in the 1850's by a Scottish chemist, Robert Angus Smith (Smith, 1872). Alongside the release of carbon dioxide, fossil fuel combustion releases sulphur dioxide and nitrogen oxide, which react with water, oxygen and other gases to form sulphuric acid, ammonium, nitrate and nitric acid.

Peatland erosion in the southern Pennines has been linked to an increase in acid deposition (Tallis, 1973). Recently, the impact of acid deposition has significantly reduced due to the focus on emission reduction and the production of renewable energy. However, the renewable energy development also has many drawbacks. In the case of windfarm development, this can cause a threat to the upland blanket bog environment through water table lowering and erosion from the disturbance and manipulation of the site (Waldron *et al.*, 2009).

2.7.3.4 Lessons learnt

Although many anthropogenic activities have negatively impacted on peatlands there is also positive work and research in relation to eroding peatlands. The understanding of the recovery of eroding peatlands and utilising healthy peatlands for carbon sequestration and other ecosystem benefits can have a positive impact as a result of anthropogenic influences on peat erosion (Buckmaster *et al.*, 2014; Martin-Ortega *et al.*, 2017).

2.8 Management of upland peat

2.8.1 Understanding linkages

There is an intrinsic link between the small and numerous headwater systems and the larger downstream ecosystems (Gomi *et al.*, 2002). Water originates in the headwaters and moves downstream, but these linkages are poorly understood. However, for successful management, restoration and protection purposes these links need to be understood and differences recognised between systems (Gomi *et al.*, 2002). Integrated management approaches are also needed in relation to the management of land and water (O'Donnell *et al.*, 2011). Runoff generation and the control of flood risk are influenced by land management practices: positive changes may include reducing stocking densities, tree planting and peat restoration but the reliable quantification of the effects is challenging.

The Convention on Biological Diversity (2004) characterised the ecosystem approach as 'a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way' (Sing *et al.*, 2015). The surrounding area should be a network of integrated land uses and the benefits of the upland peatland ecosystem services inclusive of biodiversity, sport, leisure, climate change mitigation and adaption, water quality and supply. The management of upland peat is of importance to downstream processes and cannot be considered in isolation.

2.8.2 Land management

Many peatlands have been subjected to land management practices that have not consistently been beneficial to carbon storage (Holden *et al.*, 2007a). Grazing, burning and drainage have been practised extensively on blanket mires. It is predicted that around 82 % of the blanket mires (18, 500 km^2) in the British Isles have been substantially modified as a result of management (Tallis, 1998). This can cause severe degradation with erosion, flooding, poor water quality and loss of ecological diversity (Holden *et al.*, 2007a). After the cessation of peat working, it can take greater than 100 years for the hydrological functions to be re-establishment if humans did not intervene and help the process (Seters and Price, 2002). The reestablishment of high water tables (e.g. through ditch blockage) and the re-colonisation of peat forming species are usually the initial priorities in peatland restoration (Holden *et al.*, 2004).

2.8.2.1 Afforestation in the Flow Country

The peatlands of Caithness and Sutherland in Northern Scotland cover an expanse of 400,000 ha and are often referred to as the Flow Country (Lindsay *et al.*, 1988). The 'naturalness' of the existing peatland has been questioned due to the land-use and management that has occurred over the years, such as commercial forestry operations that took place on the site in the late 70s and early 80s (Charman, 1994). One of the main moorland habitat losses in Scotland is attributable to afforestation which is the creation of a forest or stand of trees in an area where there was none previously. Around 25 % of Caithness and Sutherland peatlands have been impacted negatively by afforestation (Ratcliffe and Oswald, 1988). The rates of carbon loss as a result of afforestation on peatlands are hard to quantify for a number of reasons including differences in peatland type, fertility, and the range of drainage and ground preparation practices (Morison *et al.*, 2010; Worrall *et al.*, 2011a). The range in atmospheric emissions is highlighted in results from Flanders Moss, a lowland raised bog in Central Scotland, and a blanket bog in western Ireland which have lost a significant 4 and 17 t CO_2 ha^{-1} yr^{-1} respectively after afforestation (Byrne and Farrell, 2005; Yamulki *et al.*, 2013).

During afforestation, the previous vegetation cover declines or disappears as the tree canopy grows. This will result in greater losses of DOC, POC, dissolved CH_4 and CO_2 (Morison, 2012). The application of nitrogen fertiliser can also result in an increase in nitrous oxide (N_2O) emissions (Morison, 2012). The hydrological effects of afforestation are also location specific and depend on factors such as surface inclination and the geological setting where the peat formed (Beheim, 2006). Areas that are underlain by acid sensitive soils and bedrock are particularly sensitive to the effects of afforestation on water acidification (Puhr *et al.*, 2000). Often, the drainage of the blanket bog for commercial afforestation of non-native trees was seen as a productive economic land use for an area with few alternatives. However, conservationists highlighted the Flow Country as a habitat of international significance as it is now recognised today (Warren, 2000). Management and research has and continues to focus on the removal of trees, blocking drains, acquiring land to protect, rewetting and promoting visitors to the area, providing a source of income for the local economy (The Peatlands Parternership, 2018).

2.8.2.2 Ownership, collaboration and legislation

Much of the UK uplands are under private ownership. Land tenure is often complicated with land managed in hand or through tenancies (Moors for the Future Partnership, 2015a). Land management practices need to take into account ownership and involves collaborations between landowners and stakeholders in order to achieve sustainable outcomes. The timescale of achieving sustainable management objectives may also take many years or decades, requiring clear objectives to be set at the start. Legal and policy drivers (selection highlighted in Table 2-4) facilitate the protection and restoration of valuable habitats in the UK.

Table 2-4: Legislation relating to the protection of peatlands

No explicit laws have been introduced to protect peatlands but Great British and European legislation that protect landscapes, habitats and species assists in the conservation effort. A selection is shown below but is not inclusive of all protective measures. Source: (Open Government Licence V3.0, 2018).

Legislation	Interpretation
The Conservation (Natural Habitats, & c.) Regulations 1994	Transposed the EC Habitats Directive for Scotland into National Law.
Habitats Regulations 2010 (in relation to reserved matters)	Transposed the EC Habitats Directive for Scotland into National Law.
Conservation (Natural Habitats, &c) Regulations (Northern Ireland) 1995 (as amended)	Transposed the EC Habitats Directive for Northern Ireland into National Law.
Conservation of Habitats and Species Regulations 2017	Transposed the EC Habitats Directive for England and Wales into National Law. Consolidated the 2010 Regulations and subsequent amendments. Also transpose elements of the EU Wild Birds Directive.
The Wildlife and Countryside (Amendment) Act 1991	Protection of wildlife in Great Britain. Extends to the countryside, national parks, SSSIs and NNRs.
The National Parks (Scotland) Act 2000	Enabled the establishment of National Parks in Scotland.
National Parks and Access to the Countryside Act 1949	Established the National Park designation in England and Wales.
Amenity Lands Act (Northern Ireland) 1965	Designation of Nature Reserves in Northern Ireland.

2.8.2.3 Exploitation

Blanket bogs cover vast areas of Scotland and have long been viewed as integral to our natural heritage, historically providing dyes for tartan, flavouring for whisky and fuel for heating and industry (Scottish Natural Heritage, 2001). The values placed on bogs by society have changed as more has become known about them, so they are now widely regarded as an important resource that needs to be conserved not exploited (Brooks and Stoneman, 1997). The extraction of peat for fuel and horticulture has impacted the vegetation, hydrological conditions and carbon balance of peatlands (Lucchese *et al.*, 2010). Under optimal conditions, the greatest rate of peat formation globally is up to 3 t ha^{-1} $year^{-1}$ and 0.5-0.7 t ha^{-1} $year^{-1}$ for the UK (Moore and Bellamy, 1974; RSPB Scotland, 2009). However, peatlands are considered as a non-renewable source where exploitation exceeds the rate of replenishment.

2.9 Red deer (*Cervus elaphus*)

2.9.1 Size of deer

The interaction of humans and deer is intertwined with the management of the land. Red deer (*Cervus elaphus*) are referred to as the 'Monarch of the Glen' with reference to Sir Edwin Landseer's 1851 painting; their presence as Britain's largest terrestrial mammal supports this picture of grandeur. The Monarch refers to a 16-point antler (Table 2-5). The first postglacial records of the red deer in Britain are from c. 12,500 before present (BP) (Gowlett *et al.*, 1986; Hmwe *et al.*, 2006). The largest population of deer in Britain is found in Scotland, more specifically, the Scottish Highlands (Hmwe *et al.*, 2006). Red deer feed on grasses, herbs, mosses, buds, lichens, shrubs and trees (Mohr *et al.*, 2005), many of which thrive on or around peat bogs. Therefore, the selective grazing of deer can impact on the regrowth of peat.

Table 2-5: Development of red deer (*Cervus elaphus*) antlers

The age of the red deer stag is often linked with the development of their antlers. Antlers are shed or cast yearly when testosterone levels fall in March- April. With the progression of years larger and more branched antlers are produced up until 10 years at which point tines/points decline. Source: (Dreamstime, 2007; Alamy Stock Photo, 2009; Pressland, 2012; The Royal Society for the Protection of Birds, 2013; Macrae, 2018).

Age	Stag name	Antler (tine/point)	
Yearling	Calf	Pedicles, bony knobs (a knobber) to long spikes (a pricket)	
Second Year	Brocket	short, simple, unbranched antlers	
	Royal	12 point (6 per antler)	
From Third Year +	Imperial	14 point	
	Monarch	16 point	

The population of the four main deer species in Scotland (red, fallow, sika and roe, Figure 2-20) has been increasing. However, over the last 9,000 years the red deer have remarkably reduced in body size likely as a result of over-population from around the second half of the 20th century (Taylor and Kitchener, 2002). The estimated population of deer in Scotland is provided in Table 2-6. A study by Ritchie in 1920 compared the skeleton of an average 12 pointer (or Royal) prehistoric stag found in 1830 with those at present time (1920's). From nose to tail the prehistoric stag was 2.39 m compared with the 1920s stag at 1.70 m which is a reduction of over 25 % (Ritchie, 2015). The respective measurements for the prehistoric and 1920's stag for shoulder height were 1.37 m and 1.04 m. In 1961, Lowe further highlighted the decrease in size of the Scottish red deer after the last Ice Age (Lowe, 1961).

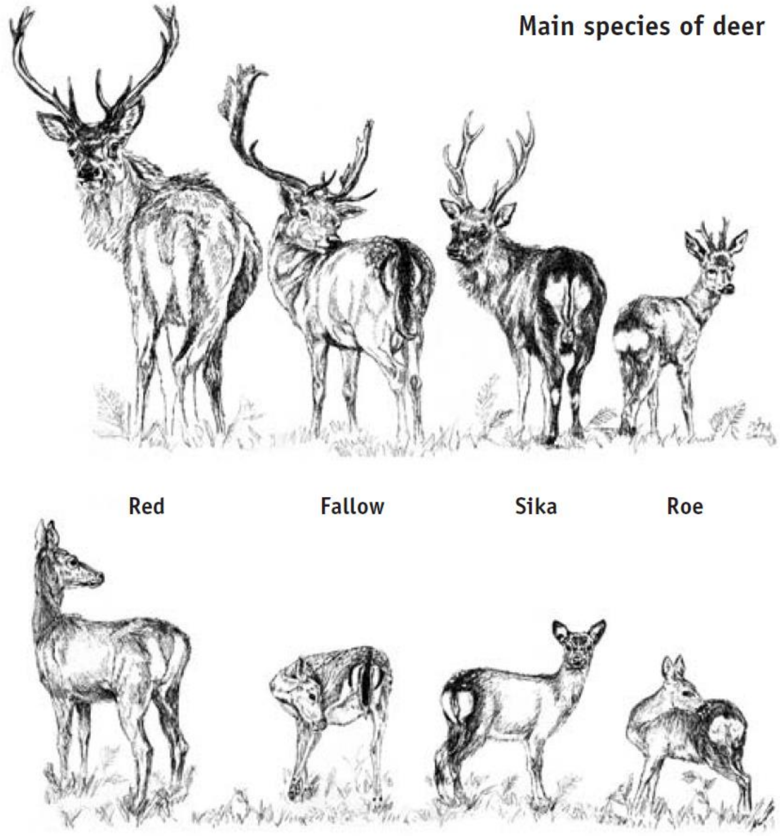


Figure 2-20: The main species of deer in Scotland with the male pictured above and the female pictured directly below

The males (stags) have antlers and are larger in size than the females (does). The family of deer are collectively referred to as Cervidae and they are known as sociable herd animals that live off an herbivorous diet (primary consumers). The red and roe are indigenous to the British Isles, whilst fallow and sika were introduced. Source: Warren (2009), p177.

Table 2-6: Estimated population of deer species in Scotland

Source: Warren (2009), p176.

Species	Estimated Population
Red deer *(Cervus elaphus)*	350,900 ± 33,300
Roe deer *(Capreolus capreolus)*	>200,000
Sika deer *(Cervus Nippon)*	>24,000
Fallow deer *(Dama dama)*	8000
Reindeer *(Rangifer tarandus)*	80
Muntjac *(Muntiacus muntjak)*	unknown

2.9.2 Territory and ranging patterns of deer

Deer are herd animals and tend to establish a territory and not leave it. A study of a red deer herd in South West Germany (1978-1981) found that during winter months, the herd ranged within 113 ha and while rutting the herd range extended to 134 ha. These areas were relatively small compared to spring and autumn home range patterns that average around 386 ha (Georgii and Schröder, 1982).

2.9.2.1 Characteristics of deer

Red deer form the largest population of deer in Europe, grazing over most of the uplands (Warren, 2009). Woodlands provide shelter and nutrients but the deer have also become accustomed to the open hill expanses (Warren, 2009). The lifespan of a wild deer in the UK is around 10 years (Conradt *et al.*, 1999). Without management, their population numbers can double in size annually under optimal conditions (Suburban Whitetail Mangement of Northern Virginia, 2017). Overpopulation can cause a 'browse line' on the vegetation structure, where the deer feed non-selectively on everything they can reach (up to a height of 1.3-1.8 m). The presence of a browse line indicates the carrying capacity of the area has been exceeded since at lower numbers the deer would feed selectively on plants chosen primarily for nutrition and taste (Bressette *et al.*, 2012). The Native Woodland Survey of Scotland reported that herbivore impacts (browsing and grazing) were responsible for greater than one third of all native woodlands that were in unsatisfactory condition (Patterson *et al.*, 2014). If there is a lack of food, the population may suffer health effects or starvation as a result. The main factors affecting deer populations are summarised in Figure 2-21.

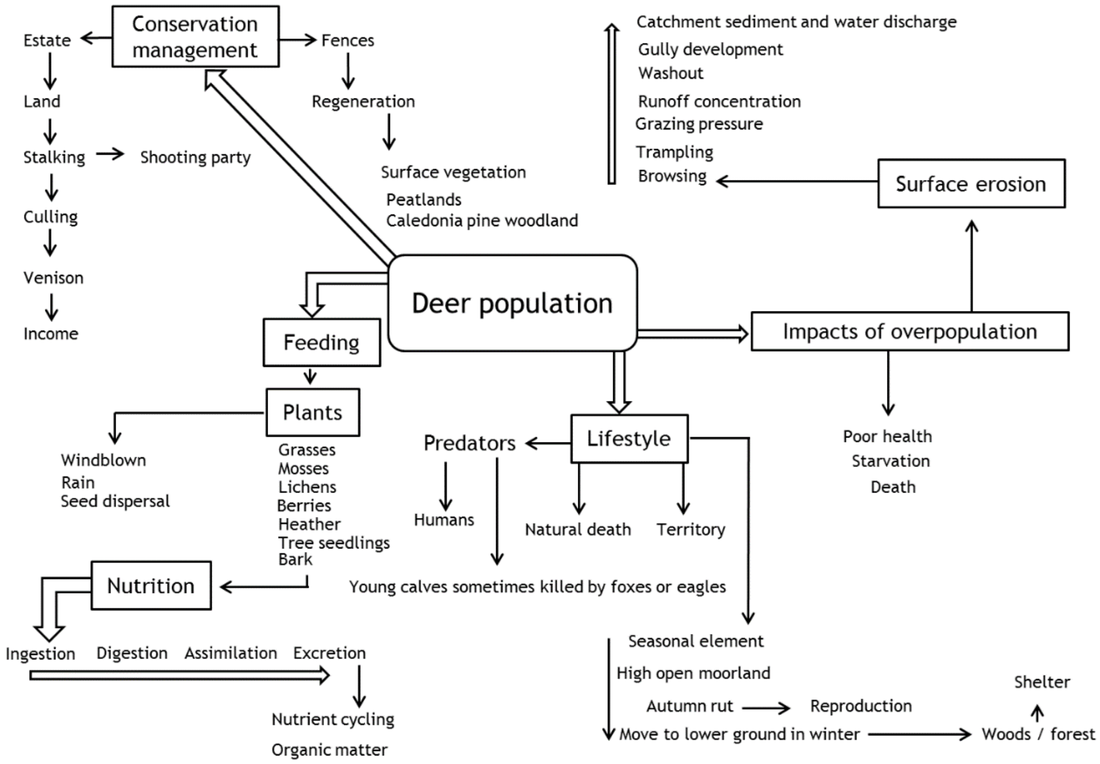


Figure 2-21: Flow diagram of how deer populations function

The main processes include feeding, lifestyle, impacts of overpopulation leading to erosion and conservation management. Within the diagram, interacting feedbacks exist e.g. poor health may lead to an organised cull and/or culling is also a means to achieving regeneration. Without natural predators, to control the population numbers, human management is required. Sustainable population numbers are required to allow for the seed dispersal and growth of new plants as well as the regeneration of habitats such as peatlands.

2.9.3 Management of deer populations

Human management of deer is a fundamental responsibility to maintain species diversity and conserve the ecosystem services provided by the forest and upland habitat (Putman and Langbein, 2003), with an emphasis also on reducing road traffic accidents. Natural predators such as the wolf are found in Europe and North America but have not existed in Scotland since the 17th century. Over the years, reintroducing the wolf to Scotland has gained wider publicity and support in relation to projects aimed at ‘rewilding the landscape’ although these carnivores alone would not remove the need for additional sustained human management of the deer population (Monbiot, 2014). The main concern regarding wolf reintroduction relates to safety of livestock. The main benefit would be controlling the deer population for the benefit of the ecosystem (Nilsen *et al.*, 2007).

2.9.3.1 Legislation relating to deer

Under the Deer (Scotland) Act 1996, which consolidated and replaced the Deer (Scotland) Act 1959, deer belong to no one and cannot be separated from the ownership of land until captured or killed at which point they are 'rendered into possession'. Voluntary control agreements are carried out by private and public landowners. If they are not carried out or the deer are causing "serious damage" then a statutory control scheme can be drawn up. Deer management operates within a framework and there are a number of stakeholders interested in wild deer management ranging from businesses, recreational and community bodies, private and voluntary organisations and public sectors (Scottish Natural Heritage, 2016a). Wild deer range freely across the landscape which can cause tension between neighbouring landowners with different management goals. The 1996 Act has since been further amended by the Wildlife and Natural Environment (Scotland) Act 2011 (WANE) and the Land Reform (Scotland) Act 2016 providing extra powers and controls relating to deer management.

2.9.3.2 Opportunities and objectives of deer management

The management of deer is predominately implemented through hunting or stalking by shooting and/or fencing to exclude deer from certain areas. The management of deer is linked with 2,520 jobs in the UK (Putman, 2012). Deer stalking can be classed by some as a sporting pastime but it is also required to control population numbers. Clients can be hosted on private estates for shooting parties and can pay around £500 to shoot a stag and £100 to shoot a hind (Putman, 2012). Landowner's objectives (of which they may have more than one) could include providing for sport shooting, grouse management or other interests such as natural heritage, agriculture, public safety and deer welfare. Deer are economically valued in terms of the opportunities they provide in employment, income from the sale of venison and contributing to the rural tourist trade (Table 2-7). In societal terms, deer are integral to Scotland's ecosystems symbolising 'the wild beauty and nature' of the forests and uplands (Scottish Natural Heritage, 2016a). In relation to the Scottish uplands, deer management is currently coordinated through voluntary Deer Management Groups (DMGs). They cover approximately 39 % of Scotland's land area (predominantly in the Highlands) and consist of 44 DMGs (Scottish Natural

Heritage, 2016a). The DMGs' purpose is to provide a structured and collaborative approach to deer management in relation to the objectives among neighbouring landowners, public and private interests.

Table 2-7: Annual summary of benefits, damages and management costs associated with deer and deer management

Note: Full Time Equivalent (FTE), attribution of Lyme disease to deer difficult (Joss *et al.*, 2003), cost of damage to vehicles per year in Scotland and England (Langbein, 2007), Scottish Rural Development Programme (SRDP) (The Scottish Government, 2013). Source: Scottish Natural Heritage (2016a).

Benefits	Cost
Sale of carcasses and processed venison	£ 7,500,000
Sporting income	£ 7,100,000
Stalking rents and other income	£ 3,000,000
Direct employment	722 paid FTE jobs
Secondary employment	Uncertain
Deer watching/ tourism	£ 100,000
Rural culture	Uncertain
Landowner benefits (pleasure from stalking)	Uncertain
Public health benefits (watch or stalk deer)	Uncertain
Existence value	Uncertain

Damage/Management	Cost
Tree damage (browsing)	Uncertain but significant
Agricultural damage (crops)	Uncertain
Damage to habitats	Difficult to monetarise
Damage from deer-vehicle collisions	>£ 16,500,000
Lyme disease	~£ 331,000
Effect on public access (from fencing, stalking)	Uncertain
Operational & capital expenditure	£ 42,600,000
Fencing	£ 4,800,000
Other deer management via SRDP	>£ 800,000
Monitoring, regulation & administration	£ 1,500,000

2.9.3.3 Deer overgrazing

The grazing of deer can affect the soil nutrient status and soil biota (Mohr *et al.*, 2005). When the vegetation cover is removed, trampling by red deer can increase wind and water erosion due to the vulnerable exposed peat area (Mohr *et al.*, 2005). There is a link between the grazing pressure placed on the surface vegetation, runoff and erosion rates. The rate of erosion is highly influenced by slope gradient (Mohr *et al.*, 2005). The formation of tracks in already intensively grazed upland areas can lengthen the ephemeral drainage network creating a quick transfer route for the water in response to precipitation (Meyles *et al.*, 2006). Rapid runoff (Orr and Carling, 2006; Holden *et al.*, 2008) and the formation of gully systems (Bragg and Tallis, 2001) can result from reduced vegetation cover as a result of overgrazing in upland areas. Sediment yields will be higher where the vegetation cover is damaged and sediment can be readily entrained (Clement, 2005). The absence of baseline data on historical and current rates of upland peatland erosion by overgrazing, recreational pressures and environmental change make the impacts hard to quantify and separate (Grieve *et al.*, 1995). However, it is recognised that grazing pressure of deer is a major driver of the upland landscape diversity and condition (Irvine, 2011). Evidence-based policy is required to manage the performance and health of the deer population within the upland ecosystem (Irvine, 2011).

2.9.3.4 Deer overpopulation

Problems for ecosystems caused by deer overpopulation occur in many places over the world such as North America, Britain, Europe, New Zealand and Japan (Takatsuki, 2009). Extreme deer browsing of understory vegetation results in sandy sedimentation of the streambed which subsequently changes aquatic insect assemblages (Sakai *et al.*, 2011). The authors concluded that deer can impact not only the terrestrial ecosystem but also stream assemblages and are described as an ‘ecosystem engineer’ (Sakai *et al.*, 2011). This was found by placing a deer exclusion fence (1.15 ha exclosure catchment) and monitoring forest floor cover, overland flow, stream environment and aquatic insect assemblages relative to a control catchment (1.66 ha). The study location was situated in a primary deciduous forest catchment in Ashiu, Japan between May 2008 to April 2009 (Sakai *et al.*, 2011).

2.10 Peatland restoration

2.10.1 Techniques for restoration

A substantial amount of work on the initiation of peat erosion has been carried out by Tallis focusing primarily on the southern Pennine peatlands located in northern England which are extensively eroded (Tallis, 1964, 1965, 1985, 1987, 1997, 1998; Tallis and Switsur, 1973). His pioneering work has focused on mitigation and restoration of erosion with techniques used such as: blocking of gullies to decrease drainage, mechanical re-profiling, heather mulch spreading and the use of nurse crops to support natural regeneration (Scottish Natural Heritage, 2011). The applicability of the techniques is site specific and favourable outcomes are most likely on slopes of less than 6^{o} (Scottish Natural Heritage, 2011). Other options including replanting vegetation and working with landowners to reduce grazing, fires and drainage have been implemented (Scottish Natural Heritage, 2011).

Research has been carried out into understanding the impacts of peatland restoration techniques on fluvial carbon losses (Fenner *et al.*, 2001; Holden *et al.*, 2007b; Armstrong *et al.*, 2010; Wilson *et al.*, 2011; Evans *et al.*, 2018). To assess the restoration success on halting erosion and reducing fluvial carbon loss, water chemistry data was collected from four study catchments in the three years prior to and following drain blocking (Wilson *et al.*, 2011). The study catchments and restoration works were based within the wider Lake Vyrnwy catchment in Wales which had been historically subject to peat extraction, hill grazing and ditch cutting associated with improvements for sheep grazing. The site was in poor ecological condition. After drain blocking restoration, a recovery towards more 'natural' conditions was concluded with a decline in specific absorbance and colour also noted (Wilson *et al.*, 2011).

A study by Armstrong and colleagues in 2009 did not find significant differences in total organic carbon (TOC) flux in a comparison between blocked and unblocked peatland drains. This highlights that better understanding is still required to gauge the full impacts of peatland restoration on carbon storage and release relating to site specific characteristics and differing timescales. In some cases, a reduction in DOC is evident after drain blocking whereas other sites will inevitably display no significant changes in DOC loss (Armstrong *et al.*, 2010). This study by Armstrong *et al.* acquired data from a UK-wide survey of blocked and unblocked drains covering 32 study sites. This is further supported by Evans and colleagues who collected fluvial carbon data from a blanket peatland in North Wales for three years prior to ditch blocking and 6 years post blocking and compared this with a control catchment. Ditches were dug in the area during the 1980s to enhance grazing opportunities for the sheep. From the results, it was concluded that there were limited impacts of the ditch blocking on DOC, POC, dissolved CO_2 or dissolved CH_4 in waterborne carbon fluxes however it was recognised that the reductions in discharge associated with the management were detected, with restoration noted as a positive outcome overall (Evans *et al.*, 2018).

2.10.2 Regeneration of peatlands

The process of regeneration (extent and morphological diversification) is hindered by the fauna such as herbivores that graze on young plants for their nutrients (Scottish Natural Heritage, 2011). A management guideline of 15 deer per km^2 was proposed (Scottish Natural Heritage, 2011). The annual rate of recruitment (population increase) needs to be less than or equal to annual culls to maintain or reduce the population. To reduce the population, the annual cull has to be greater than the maximum calving rate of 40 %. The calving rate is the number of calves born for every 100 hinds (1+ years old) with a Scottish average of 20-40 % (Scottish Natural Heritage, 2013).

The acknowledgement of high deer numbers and the negative impact on supporting sustainable ecosystems has been around for over 150 years (Forest Policy Group, 2016). Since 1959, the Red Deer Commission (RDC) has voiced concern, disappointment, pleaded and actioned at reform. This has been directed at estate owners with regard to the emphasis on excessive sporting to the detriment of effective conservation management. The ecological public interest is conflicted with the economic private interest of maintaining high numbers for shooting interests. The estate agents add a capital value of £40 to £50,000 to the value of an estate for each ‘sporting’ stag shot underpinning this conflict (Keegan and Daniels, 2013).

2.10.3 Peatland water balance

The water tables of peatlands are naturally high and a raise in level as a result of restoration activities may be considered minimal. However, the increased surface roughness on re-vegetated surfaces may lead to a reduction in overland flow velocities (Holden *et al.*, 2008). The formation of blanket bog is dependent on a positive water balance, leading to a mostly water-logged site, low rates of evapotranspiration due to low annual temperatures and high frequency of rainfall (Artz *et al.*, 2014). Palaeoclimatic research has informed this understanding, but these conditions would be required over the first few years to decades for restoration activities in the current climate to have a chance of success of peat accumulation.

Numerical models have been used by researchers to identify potential peat forming areas, where blanket bog regeneration may be favoured or indeed where it is constrained by climate, peat harvesting or renewable energy developments (Clark *et al.*, 2010b; Smart *et al.*, 2010). A prevailing output from the models is that maximum resilience to projected climatic conditions is found in the west and northern parts of Scotland. In balance, these modelling tools, whilst helpful in their guidance, should be seen as suggestive in relation to blanket bog regeneration and not to form the only reason for selecting a site due to the lack of understanding of the feedback mechanisms of other features of blanket bog diversity (Artz *et al.*, 2014).

2.10.4 Benefits of peatland restoration

The restoration of peatlands has numerous benefits including: the storage of carbon, reduction of flood risk, reduction in wildfires from the waterlogged soil and an increase in biodiversity (Scottish Natural Heritage, 2011). It is often difficult to establish the success of peat restoration projects due to the difficulty of determining when a peatland is working to its full potential (Holden, 2005d). The idea that peatlands have a ‘tipping point’ has been well documented in the last six years (Lenton, 2012; Artz *et al.*, 2014; Reed *et al.*, 2014; Dieleman *et al.*, 2015; Reed, 2017). This point is irreversible resulting in a change towards other ecosystem types. The priority for management and restoration should therefore focus on equipping our existing peatlands with resilience to gradual climate change. The goal for degraded sites is to reduce current losses of carbon and biodiversity with a longer-term aim of improving carbon sequestration and biodiversity benefits, which may also apply to peatlands in good condition.

Peatland disturbance (e.g. drainage, extraction, fire) can cause on a human time scale, irreversible impacts in peatland function. Guo and Gifford (2002) state that it may take decades or even centuries to reclaim soil carbon stocks post land use change disturbance. This creates difficulty in assessing success and shaping strategies for peatland restoration whilst in some cases restoration may also intensify carbon loss (Holden, 2005d). Restoration to what is a question that should be asked in each situation: is the outcome to maintain ‘current ecological function' (Charman, 2002) or to allow the peatland ecosystem to develop in new directions (Holden, 2005d)?

2.11 Literature review summary

Peatlands are complex ecosystems that include important feedback mechanisms. Their function is driven by many physical, chemical and biological processes. Understanding the peatland ecosystem requires an interdisciplinary approach linking various specialisations between biology, biochemistry, ecology, palaeoecology, environmental science, hydrology and modelling as well as collaborating with disciplines outside these fields. The hydrological condition of an upland blanket bog is a result of the amount of rainfall input into the system versus the loss of water through evaporation, surface and subsurface runoff (Holden *et al.*, 2004). The total rainfall over a particular area cannot be controlled but it does control the sensitivity of the peatland to damage and should be taken into account when considering remediation or restoration strategies (Holden *et al.*, 2004).

Peat erosion is a natural process but external disturbances such as climate change and human activities can increase blanket bog degradation through altering the vegetative cover (Bragg and Tallis, 2001). The production and transport of sediment is the result of a reduced vegetative cover (Li, 2014). The conservation and restoration of peatlands is a focal point for carbon sequestration and other ecosystem service benefits. It is important to anticipate that blanket bogs may be placed under severe stress under future climate change scenarios that facilitate degradation and erosion. The mitigation of and adaptation to these changes is something that should be considered when questioning the future health of the peatland ecosystem.

3. Site characterisation

Within the site characterisation, the study site is described in relation to its geography. The surrounding human and physical features are highlighted to showcase the diversity of interacting factors that are associated with understanding and appreciating the Mòine Mhór.

3.1 History

In order to place the study site in space and time, a brief history of the Mòine Mhór up to the current day is now outlined.

3.1.1 Place names

Sir Archibald Geikie (1835 – 1924) once said that "*The present is the key to the past*" (Taylor and Kitchener, 2002). To understand what is happening today we first must recount the past land use of the Mòine Mhór and more broadly what has happened at Glen Feshie. Place names themselves can disclose a snapshot descriptor of the land as it once was, making it possible to tell a lot about the place from its name alone (Table 3-1). The Gaelic translation of Glen Feshie itself means 'glen of bog streams', a literal description of the source of the Feshie water (Murray and Watson, 2015). The names suggest the Mòine Mhór to be a vast boggy area surrounded with rough dramatic scenery and high topographical areas with some exposed surface geology.

Table 3-1: Place names (Gaelic to English translation) and their location on or around the study site

Gaelic Name	English Translation	Grid Reference
Mòine Mhór	Great moss	NN 89800 95312
Caochan Dubh	Dark water	NN 89805 94582
Feshie "feithsithean"	Fairy water	NN 84397 92687
Coire Garbhlach	Corrie of the rugged place	NN 87755 94645
Meall Dubhag	Lump-hill of dark place	NN 88050 95567
Fionnar Choire	Cool/chilly corrie	NN 88057 94872
Càrn Bàn Mòr	Great white stony hill	NN 89377 97192
Allt Sgairnich	Scree streamlet	NN 90802 96231
Cnap nan Laogh	Hill of the calves	NN 90735 94209
Coire Mharconaich	The horse place	NN 91100 93434
Druim nam Bò	Ridge of the cow	NN 87391 92150
Coire Domhain	The deep corrie	NN 87381 92775
Mullach Chlach á Bhlàir	Summit of the stony plain	NN 88299 92691
Meall nan Sleac	Lump-hill of the declivity	NN 86807 94451

3.1.2 Land use

There is evidence of human activity in the form of archaeological ruins dating back 400 years in Glen Feshie (Marshall, 2013). Between 1942 and 1946 the army took over Glen Feshie and the lodge and used it as a World War II military training ground (Figure 3-1) (Marshall, 2013). Glen Feshie is a much quieter environment today but still draws in the footfall from hill walkers, bikers and nature lovers alike. The Glenfeshie Estate buildings are located at Carnachuin. This and Achlean, a small pastoral farm of mixed cattle and sheep, are the two main occupied settlements south of Tolvah (Figure 3-1).

A lot of science and research is carried out in and around Glen Feshie. Examples include research on the braided River Feshie (Young, 1975; Ashworth and Ferguson, 1989; Soulsby *et al.*, 2004), archaeological studies (Peteranna and Fraser, 2010), ecological studies (Watt and Jones, 1948; Mcvean, 1961), climatic monitoring (Newbigin, 1906), to highlight a few. Research work from around Glenfeshie was compiled as part of understanding the area local to the study site. The list gathered comprised of over 60 publications that have been carried out in the area namely relating to the River Feshie, including the geology, climate, and management of the surrounding land (for reference these publications have been summarised in a table format in Appendix A). Therefore, the influence of us as scientists researching the land over time must also be acknowledged. The Mòine Mhór contribution to the publication list was found to be small and indicates space for further understanding relating to the processes taking place in the upper reaches of the catchment.

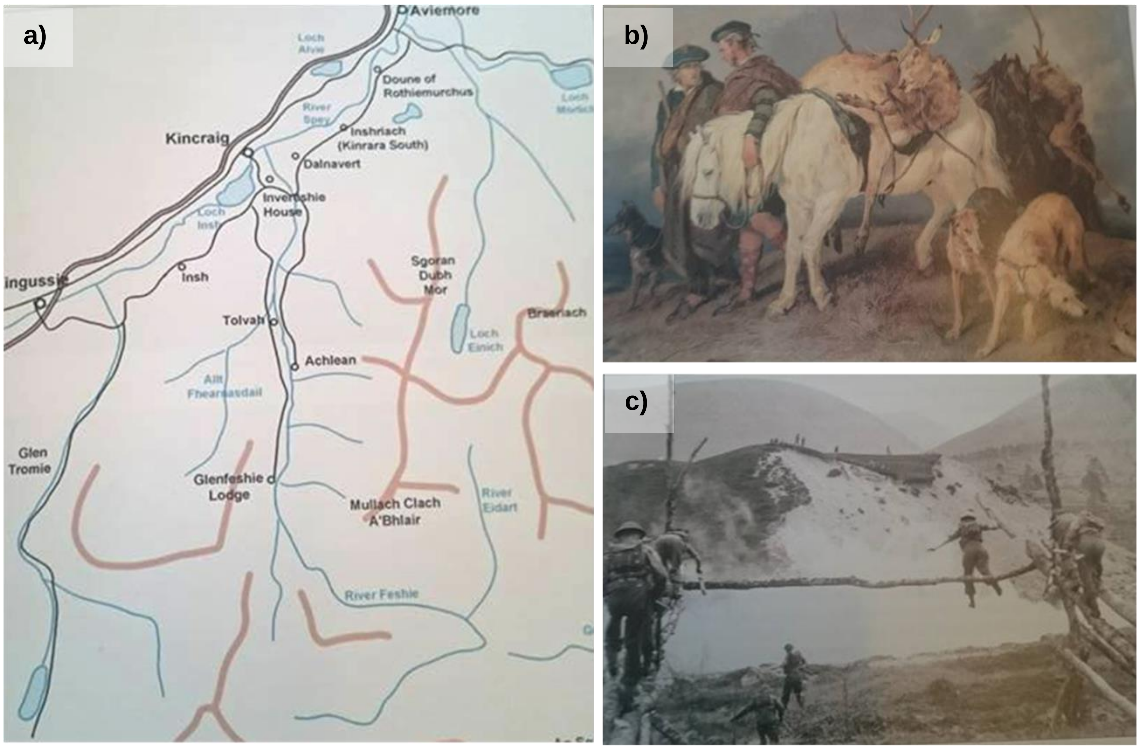


Figure 3-1: Glen Feshie as seen by others

(a) The surrounding area of Glen Feshie and the main settlements in the upper reaches of Glen Feshie; (b) *Return from deer stalking* 1827 – from the collection of the Duke of Northumberland (the two characters are thought to be Charles Mackintosh and Malcolm Clark from Glenfeshie); (c) Assault course at the Highland Fieldcraft Training Centre Glenfeshie in 1944. Source: Marshall (2013).

3.1.3 Ownership of Glenfeshie estate

Changes in estate ownership can impact significantly on the land management of an area (Fielding and Haworth, 1999). The potential negative impact of deer on land management with particular reference to overpopulation was outlined in Section 2.9 of the literature review and can be linked with poor estate ownership. Glenfeshie sporting estate has had six different owners from 1964 – 2016 (Royal Scottish Geographical Society, 2015). Glenfeshie estate was acquired by the present owner, Mr Anders Holch Povlsen in 2006 (Figure 3-2). The current owner has nine other Scottish estates owned through his Scottish holding company Wildland Limited. Under the present ownership, the work of the estate has become focused on conservation, notably the regeneration of the native Caledonian pine trees. This has involved the continued culling of deer but has since seen the positive benefits reaped notably in the regeneration apparent across the Glen to date (Figure 3-11). The ecologically important site with rare habitats for flora and fauna is also benefiting from this sympathetic management (RSGS, 2015).

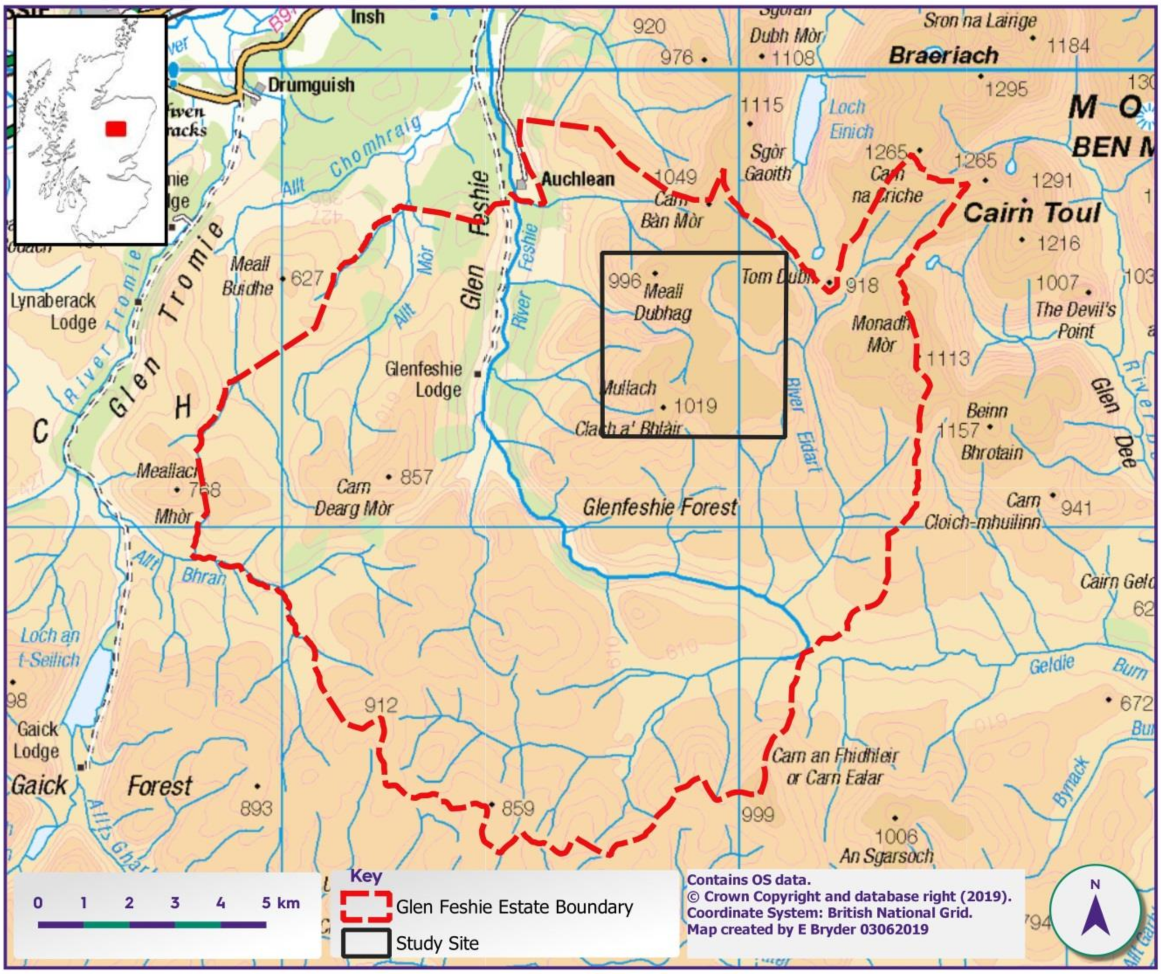


Figure 3-2: Boundary of Glenfeshie estate as of 2015 covering 43,000 ha

The location of the study site in Scotland is shown in the inset map. The boundary of Glenfeshie estate extends from Auchlean in the north and encompasses the Glenfeshie forest and surrounding hillsides. The upper reaches of the River Eidart sit within the estate boundary and the braided River Feshie flows through the centre of the estate grounds.

3.2 Mòine Mhór topography

The study site is located to the east of the River Feshie next to the Mullach Chlach á Bhlàir and is located centrally within the estate boundary (Figure 3-2). The Mòine Mhór (900-950 m) is an upland blanket bog located in the south-west of the Cairngorms National Park, Scotland (57°01’52.09”N; 3°42’24.29”W). The Cairngorm Mountains form the largest area of montane environment in the UK (Barron *et al.*, 2011). The Mòine Mhór was selected as the study area for its attributes as a high-altitude peatland (Figure 3-3) where the spatial variability within and between catchments could be explored. The position and location within Glenfeshie estate also worked well with existing collaborations already in place prior to this study. The overall peatland is estimated to cover ~1500 ha, with peat depths up to 1.5 m and an estimated total of ~4 million m^3 of peat. This is based on 25 cm mean peat depth from field study conducted by Dr Olivia Bragg in 2013 (unpublished). This study focuses on the streams situated on the Mòine Mhór plateau which drain into the River Feshie forming part of the Spey catchment area (3,000 km^2).

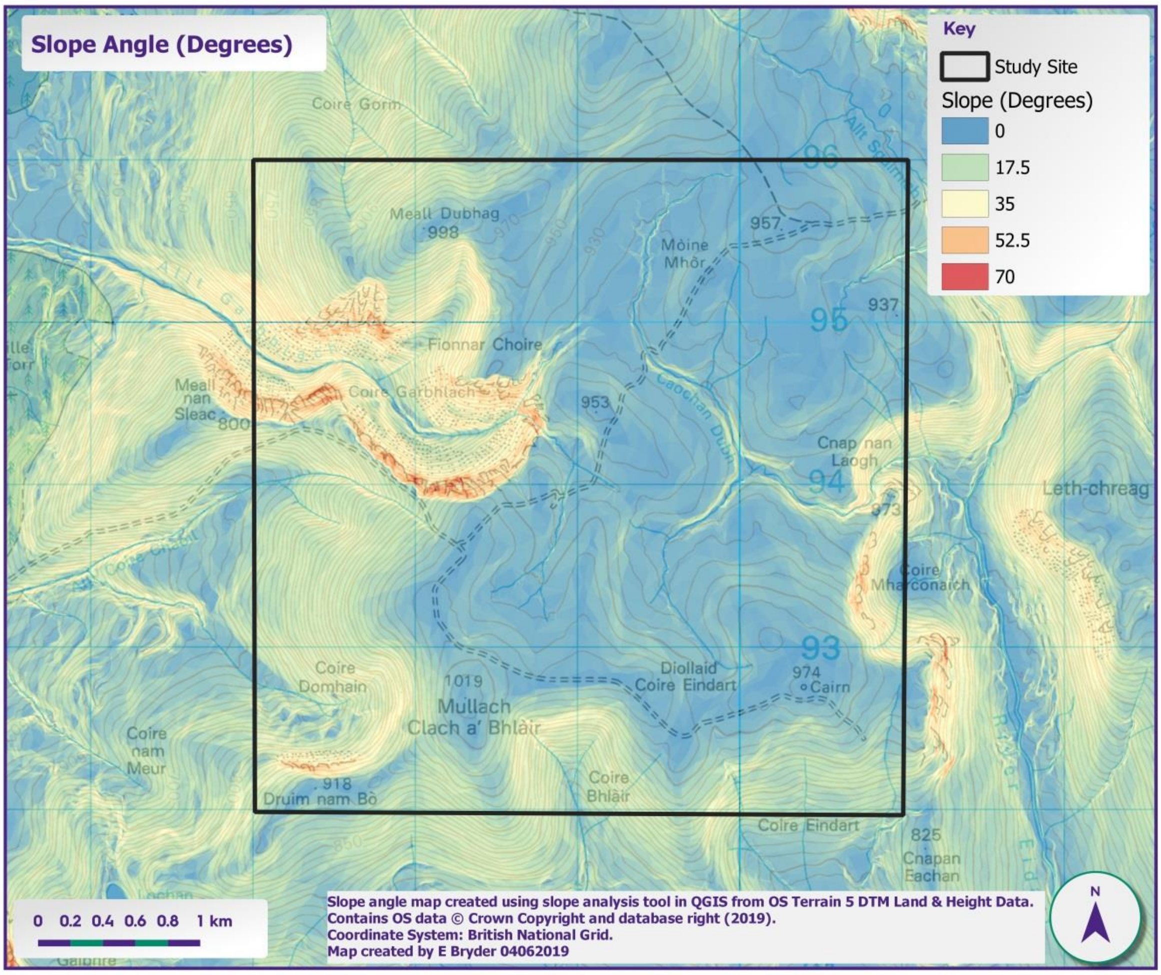


Figure 3-3: Mòine Mhór study site slope angle

As displayed by the colour gradient changes in slope angle, the Mòine Mhór plateau is an upland blanket bog bounded by Meall Dubhag (998 m AOD) to the north, the Coire Garbhlach to the north west, the Mullach Chlach á Bhlàir Munro (1019 m AOD) to the south and Cnap nan Laogh (873 m AOD) and Coir Mharconaich to the east.

3.2.1 Mòine Mhór soils

The national soil map for Scotland (Figure 3-4) highlights two main soil types within the study area. The montane soils of the Mòine Mhór plateau have been mapped as subalpine podzols with dystrophic blanket peat. The immature soils of the steep, rocky Coire Garbhlach have been mapped as peaty rankers with lithosols (The James Hutton Institute, 2013).

The key characteristics of the two major soil sub-groups found within the study site were taken from the Scottish soil classification (2013). Located on the plateau and characteristic of an exposed site, subalpine podzols have a thin peaty surface layer often overlying a leached grey subsoil and iron pan layer. Freeze-thaw processes result in a porous and loose soil structure. Areas were mapped as dystrophic blanket peat which can be described as poorly drained, acidic, nutrient poor and supporting vegetation communities dominated by heathers and nutrient poor grasses. The lithosols mapped in the Coire Garbhlach are shallow in depth with rock found within 10 cm of the surface. Areas of peaty rankers also mapped within the Coire Garbhlach can be described as shallow wet soils with an organic surface layer <50 cm thick overlying a weakly developed, wet subsoil on to rock (Scotland's Environment, 2017).

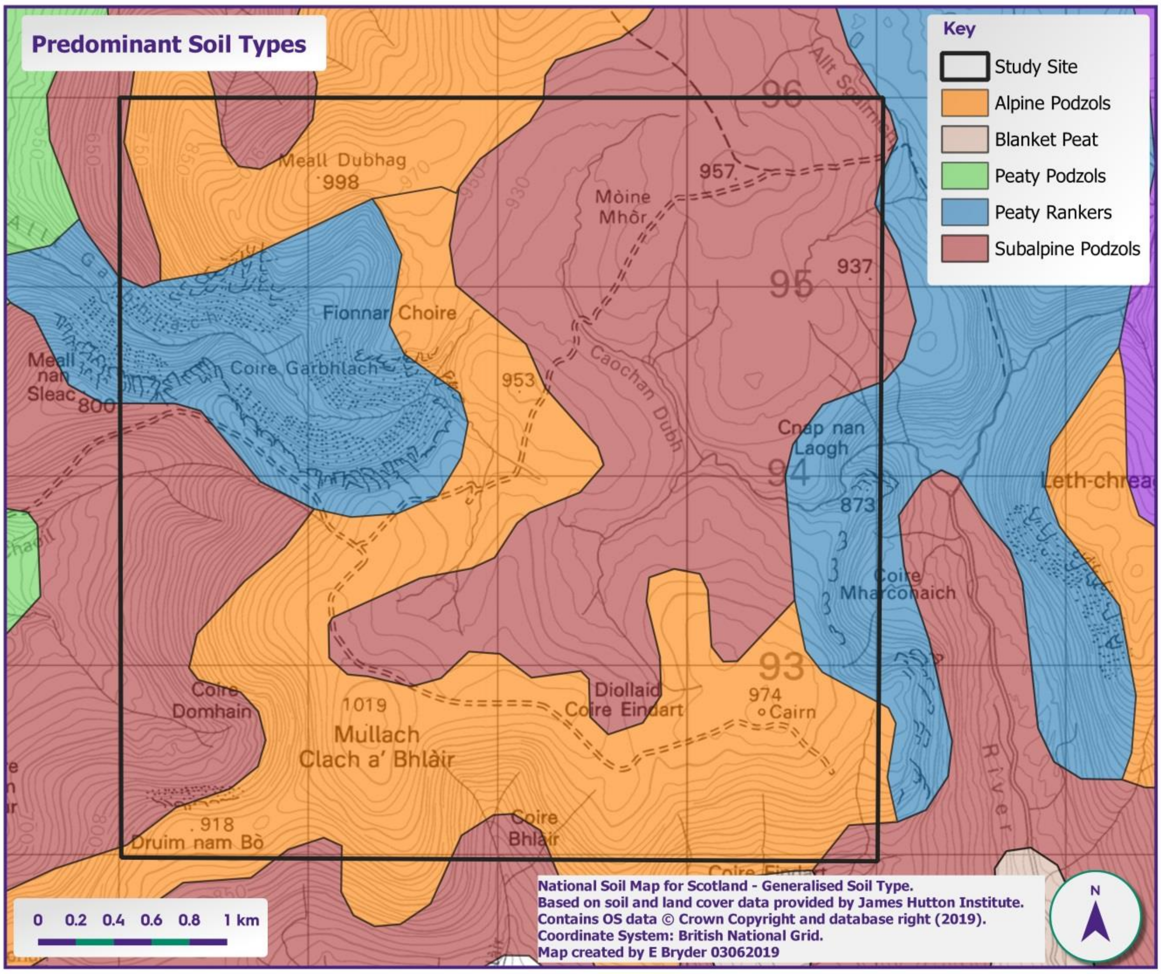


Figure 3-4: Predominant Soil Types

The centre of the Mòine Mhór plateau is dominated by subalpine podzols with the topographic highs including Mullach Chlach á Bhlàir mapped as alpine podzols. The steeper corries are mapped as peaty rankers.

3.2.2 Classification of the Mòine Mhór peatland

According to SNH peatland Classification, the Mòine Mhór is classed as a mix of Class 1, Class 2 (both nationally important) and a small portion on the peripheries of Class 3 and is therefore of high conservation value (Scottish Natural Heritage, 2016d). Mineral soil is highlighted in the rocky catchments of the Garbhlach and surrounding Munros such as the Mullach Chlach á Bhlàir (Figure 3-5).

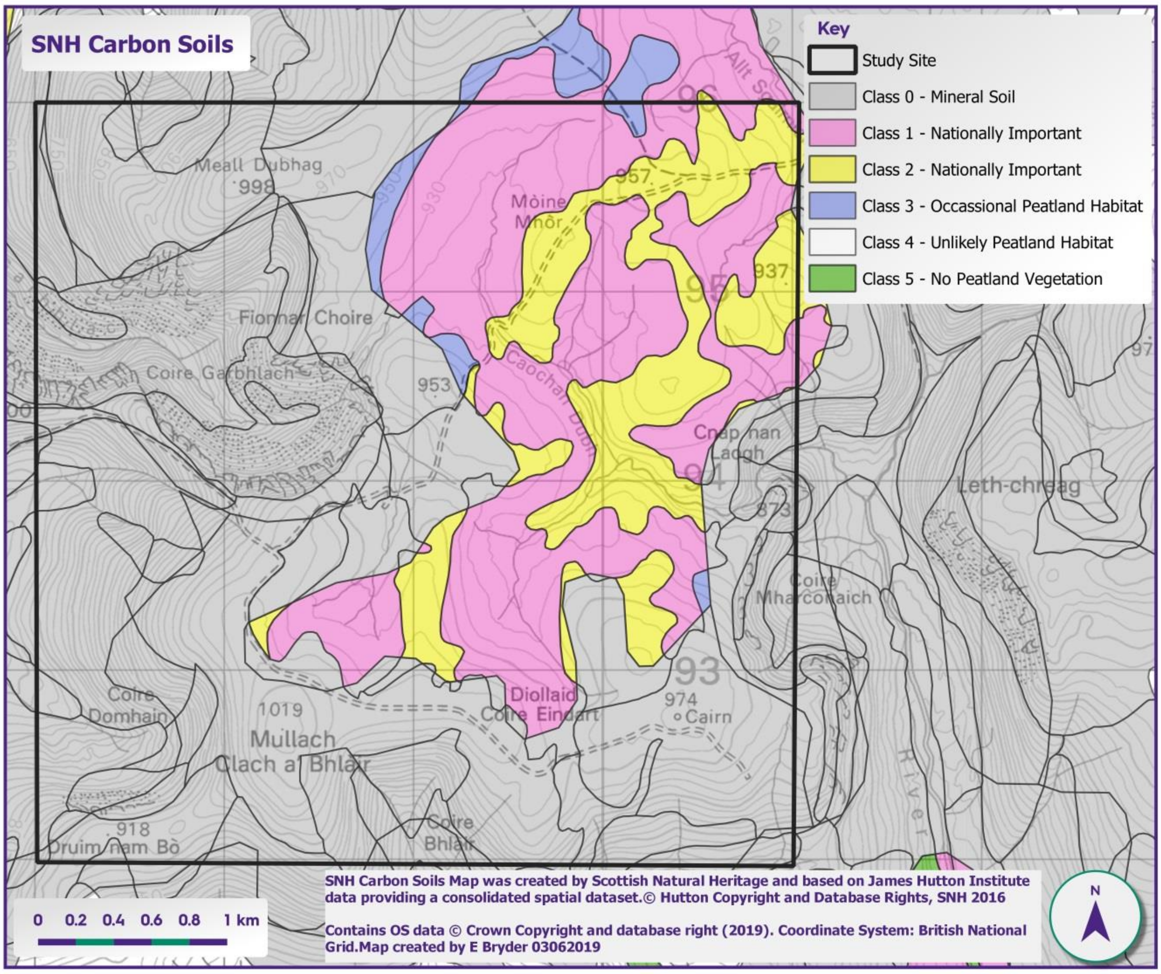


Figure 3-5: Classification of peatland habitat on the Mòine Mhór

The Mòine Mhór plateau is predominately located in Class 1 and Class 2 peatland habitat. The colours in the map correspond with the legend opposite and a descriptive legend table provided previously in Figure 2-1 (Scottish Natural Heritage, 2016c; d).

3.2.3 Condition of the Mòine Mhór

Site condition monitoring by SNH has identified the upland blanket bog habitat as unfavourable with no change since the last visit in April 2007 (Scottish Natural Heritage, 2016e). The feature pressure is recorded as over grazing and trampling by deer. The Mòine Mhór has been designated as a Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC), Special Protection Area (SPA), National Nature Reserve (NNR) and a National Scenic Area (NSA) recognising its national and international importance for conservation (Figure 3-6) (Scottish Natural Heritage, 2016e).

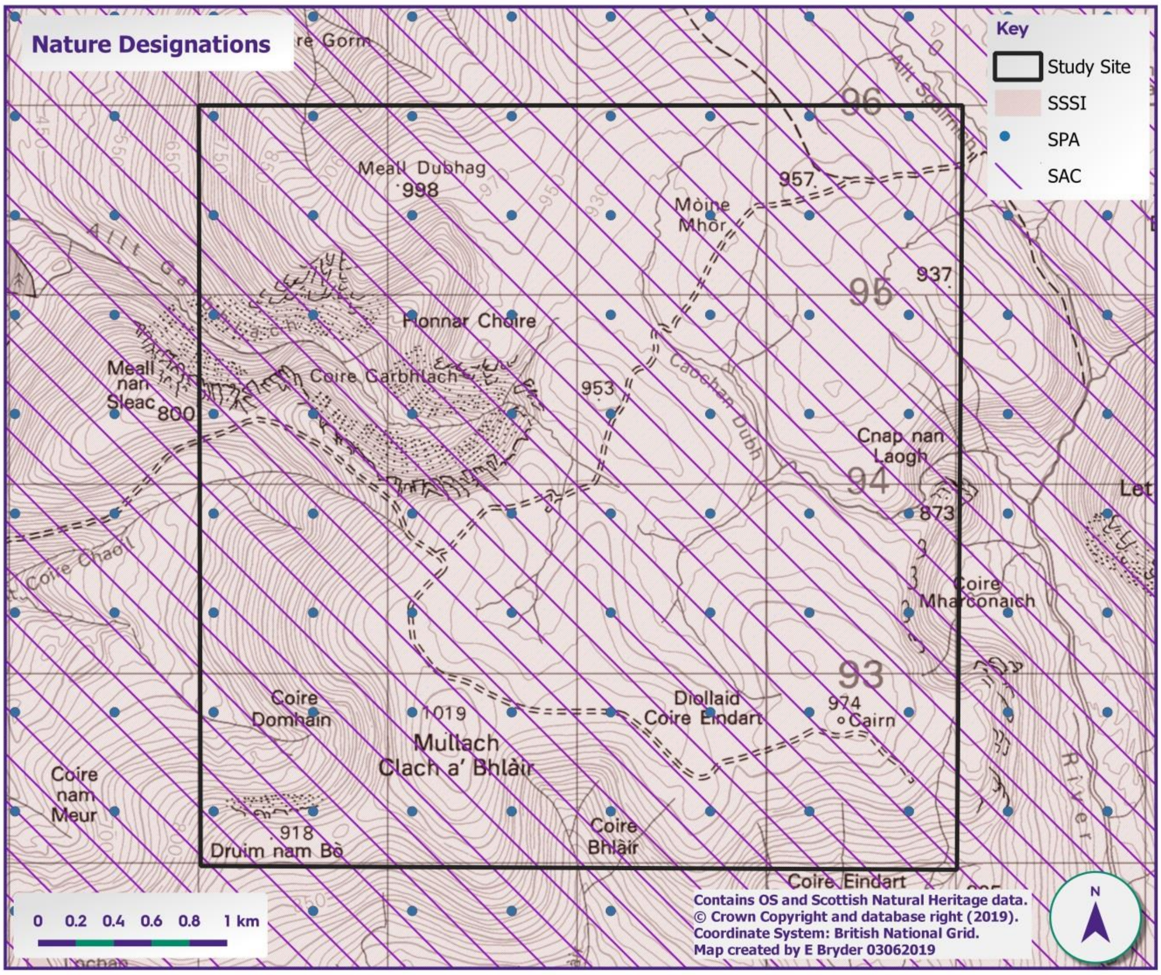


Figure 3-6: Designated study site

Including its positioning within the Cairngorms National Park, the Mòine Mhór plateau lies within the Cairngorms SSSI, Cairngorms SAC and Cairngorms Massif SPA.

The areas of bare peat visible on aerial photography for the study area of interest were delineated in QGIS to give an indication as to the total extent of bare peat coverage per monitored catchment area (Figure 3-7). The percentage of bare peat per catchment area ranged from 16 % in the rockier and steeper Garbhlach north east catchment to 42 % bare peat coverage in the Caochan Dubh upper catchment located in the centre of the plateau.

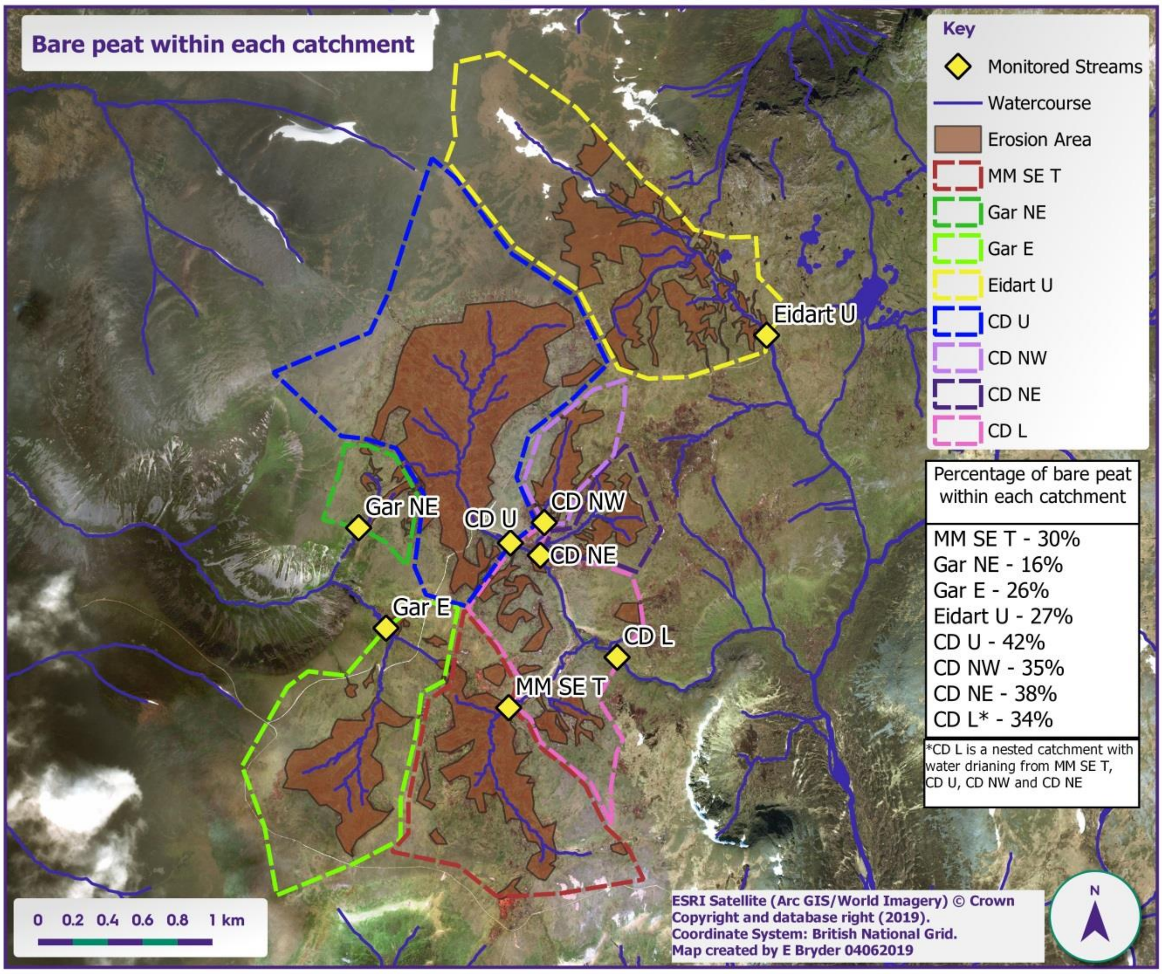


Figure 3-7: Bare peat on the Mòine Mhór

Monitored streams are highlighted with yellow diamonds with the corresponding catchment areas delineated in colour. Stream acronyms are explained in Table 4-1. Bare peat areas are shown in brown with the percentages per catchment area displayed above. Note that CD L is a nested catchment with water draining from MM SE T, CD U, CD NW and CD NE. Contains ESRI Satellite Data, date of image unknown, estimated 2007.

3.3 Mòine Mhór geology

The bedrock geology of the study site is Dalradian schist (Figure 3-8), differing from the granite which makes up the rest of the Cairngorms massif (Gordon *et al.*, 2006) whereby both are highly resistant to weathering. The Dalradian rocks are around 700 million years old and are some of the oldest rocks in the Cairngorms whilst the Cairngorm granite formed around 425 million years ago and represents the second largest single area of granite in Britain (Gordon *et al.*, 2006). The drift geology comprises of sand, gravel and mud deposited as the last glaciers melted in the Cairngorms around 11,500 - 400 years ago, allowing plants to recolonise and stabilise the earth surface (Golledge et al., 2008; Harrison et al., 2014; Kirkbride et al., 2014).

In addition to the underlying bedrock and glacial deposits, the local climatic conditions provided a favourable environment for peat formation to take place on the elevated Mòine Mhór. Today, the vegetation consists of a patchy mix of grasses, mosses, mire, heath and riparian communities with extensive areas of bare and eroding peat also present (Table 3-2).

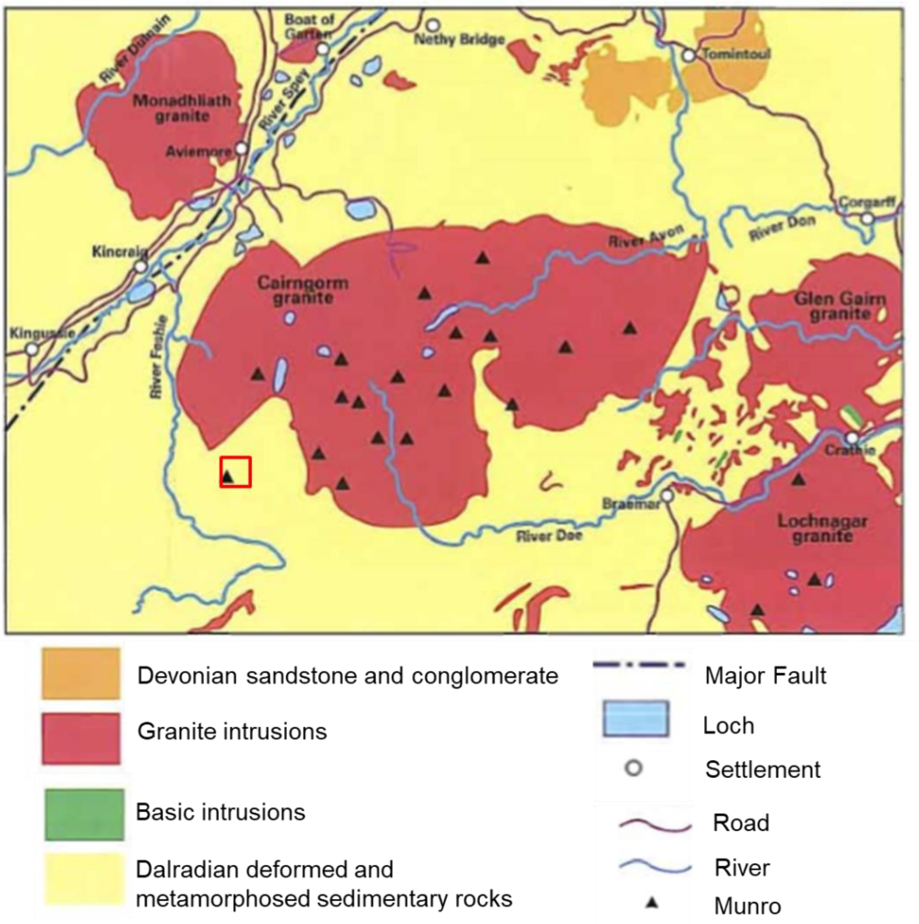


Figure 3-8: Solid geology map showing Cairngorm granite (red) and Dalradian rock (yellow)

The Glenfeshie Mòine Mhór (red outline) positioned next to the Mullach Chlach á Bhlàir (Munro) is located on Dalradian schist. Source: Gordon *et al.,* (2006), p.3.

Table 3-2: Summary of the main characteristics of the study site

The study site of the Mòine Mhór plateau has been summarised by its dominant characteristics as it is placed in the landscape today.

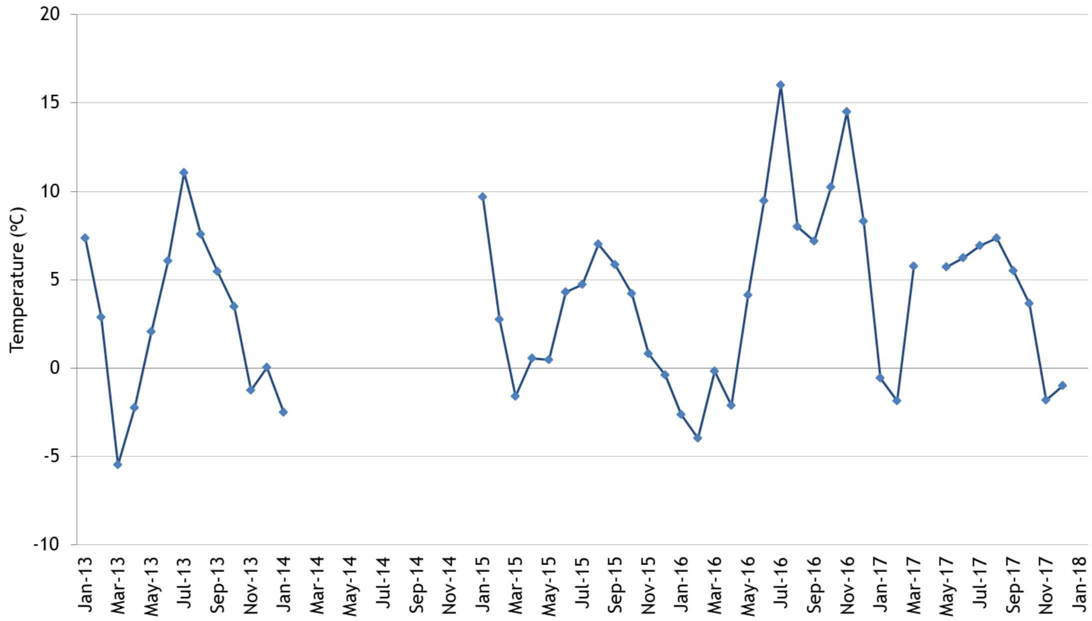
Characteristics	Mòine Mhór, Glenfeshie
Blanket peat	Covers ~1500 ha, with peat depths up to 1.5 m. Peat depths are generally between 0 - 1.5 m.
Elevation	Highest summit: Càrn Bàn Mòr (1052 m). Altitude range studied: 900 m to 950 m.
Long-term mean precipitation*	977.1 mm per annum.
Vegetation cover	Dominated by *Eriophorum angustifolium* (common cotton grass), *Nardus* (mat grass), *Racomitrium* (woolly-hair moss), *Carex bigelowii* (stiff sedge) and *Sphagnum* spp.
Main land use	Deer stalking and recreational (mostly hill walking).
Geology	Dalradian schist forms the high area of the Mòine Mhór.

* Taken from the Aviemore Met Office station average for climate period 1981 – 2010 located at lat/long 57.206, -3.827 at 228 m above mean sea level, note at a lower altitude than the study site.

3.4 Cairngorm AWS

Wind speed and temperature data available from the automatic weather station (AWS) situated on the Cairn Gorm summit (1245 m, 57°N, 3°W) is displayed in Figure 3-9 and Table 3-3. The Cairngorm AWS has been maintained and operated by Heriot-Watt University, Physics Department since 1977 (Crowder and MacPherson, 2016). The Cairngorm AWS is positioned 13.5 km north east from the study site (at 950 m) therefore the mean annual air temperature of 2013, 2015, 2016 and 2017 of 3.08, 3.19, 5.75 and 3.26 °C respectively give a good indication of the climate on the plateau. The extremes of the climate are reflected in the lowest recorded temperatures and highest recorded wind speeds across the dataset of -12 °C and 53.3 m/s respectively (Table 3-3). Freezing temperatures are recorded across the full year in the transitional subarctic climate.

a)



b)

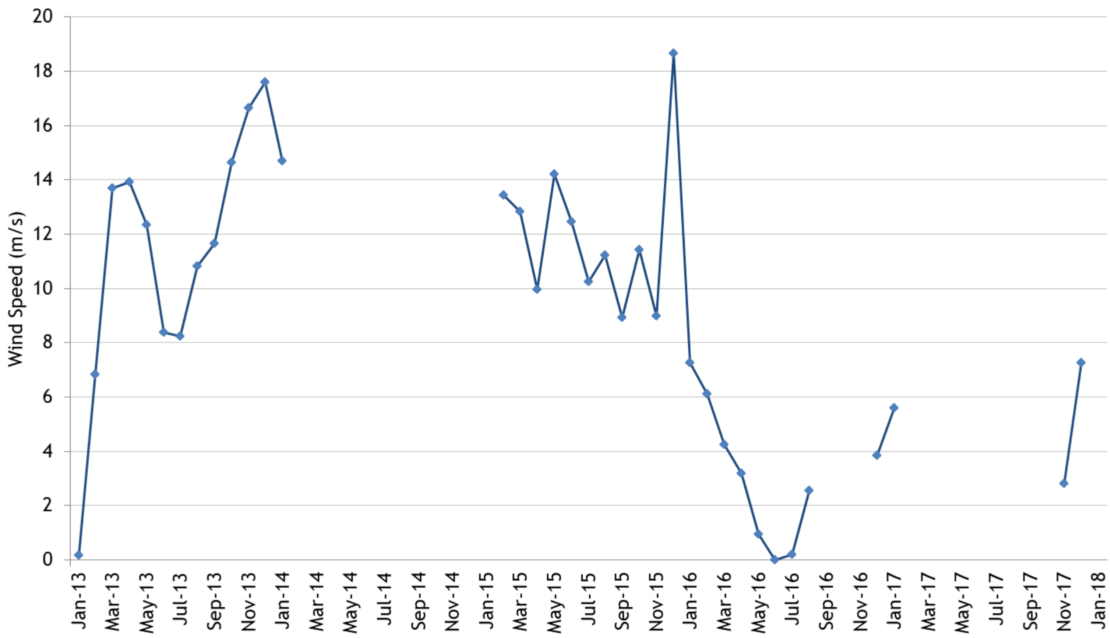


Figure 3-9: Cairngorm Automatic Weather Station data

Cairngorm weather station data for air temperature in °C (a) and wind speed in m/s (b). Values are monthly means of data recorded every 30 minutes. Due to a fault with the weather station in 2014, no data is shown for this period. A fault also occurred with the anemometer from Feb-Oct 2017. Mean annual temperature and wind speed was 3.83 °C and 9 m/s respectively. Note: Accuracy of dataset cannot be guaranteed. When fan fails on the thermometers, temperatures may read several degrees higher in light winds (< 4.47 m/s) which happened in Jan and Feb 2013. Source: Crowder and MacPherson (2016).

Table 3-3: Cairngorms Automatic Weather Station

Summary statistics from Figure 3-9 (a) and (b) for weather data collected from Cairngorms AWS across study period. Data gaps are shown by a dash, negative temperatures are shown in blue and wind speeds over 44.7 m/s (100 mph) are shown in red, the lowest temperature and highest wind speed of -12°C and 53.3 m/s are highlighted in **bold**. Source: Crowder and MacPherson (2016).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temp (˚C)	**2013**	7.4	2.9	-5.5	-2.3	2.1	6.1	11.1	7.6	5.5	3.5	-1.3	0.0
	2014	-2.5	-	-	-	-	-	-	-	-	-	-	-
	2015	9.7	2.8	-1.6	0.5	0.5	4.3	4.7	7.0	5.8	4.2	0.8	-0.4
	2016	-2.6	-4.0	-0.2	-2.1	4.1	9.5	16.0	8.0	7.2	10.2	14.5	8.3
	2017	-0.6	-1.9	5.8	-	5.7	6.2	6.9	7.3	5.5	3.7	-1.8	-1.0
Min Temp (˚C)	**2013**	-6.0	-9.9	**-12.0**	-11.6	-6.2	-1.4	-0.3	0.6	-2.7	-3.5	-7.8	-11.0
	2014	-4.5	-8.8	-8.3	-8.6	-6.4	-4.3	-1.0	1.8	-0.8	-2.8	-9.4	-6.6
	2015	-10.3	-9.0	-9.0	-8.3	-6.2	-1.6	1.5	-1.2	-1.2	-0.6	3.2	-7.7
	2016	-10.3	-9.0	-9.0	-8.3	-6.2	-1.6	1.5	-1.2	-1.2	-0.6	3.2	-7.7
	2017	-9.8	-9.6	-9.7	-	-0.8	-0.7	1.0	1.0	-0.4	-3.5	-9.8	-9.6
Mean Wind Speed (m/s)	**2013**	0.2	6.8	13.7	13.9	12.3	8.4	8.3	10.8	11.7	14.6	16.7	17.6
	2014	14.7	-	-	-	-	-	-	-	-	-	-	-
	2015	-	13.4	12.8	10.0	14.2	12.5	10.2	11.2	8.9	11.4	9.0	18.7
	2016	7.3	6.1	4.2	3.2	0.9	-	0.2	2.5	-	-	-	3.8
	2017	5.6	-	-	-	-	-	-	-	-	-	2.8	7.3
Max Wind Speed (m/s)	**2013**	10.2	35.2	50.0	**53.3**	43.8	34.8	33.6	36.4	43.4	40.9	42.2	46.7
	2014	46.7	36.9	-	-	-	-	-	-	-	-	-	-
	2015	-	46.7	46.3	38.9	38.9	40.9	30.3	38.9	39.3	48.3	49.6	47.1
	2016	23.3	23.6	19.4	18.2	19.0	7.6	8.9	19.7	-	-	-	25.7
	2017	35.9	-	-	-	-	-	-	-	-	-	16.8	24.0

3.5 Allt a' Mharcaidh ECN AWS

The Allt a' Mharcaidh AWS is part of the UK Environmental Change Network (ECN). This AWS has been maintained and operated by the Centre for Ecology and Hydrology (CEH) since 1986. Precipitation, temperature and wind speed data from the AWS situated in the Allt a' Mharcaidh (600 m, NH 89596 BNG 02386) is displayed in Figure 3-10. The catchment area drains to the River Feshie and is situated in the north-west of the Cairngorms, ~8.0 km from the Mòine Mhór. The mean annual precipitation is around 1100 mm of which 30 % falls as snow during the winter months (Oct-Mar) (Helliwell *et al.*, 1998). The mean monthly temperature ranges from -0.17 °C in January to 10.87 °C in July. The highest wind speed was recorded in December 2013 (14.82 m/s or 33.15 mph) with the mean wind speed recorded as 6 m/s or 13 mph.

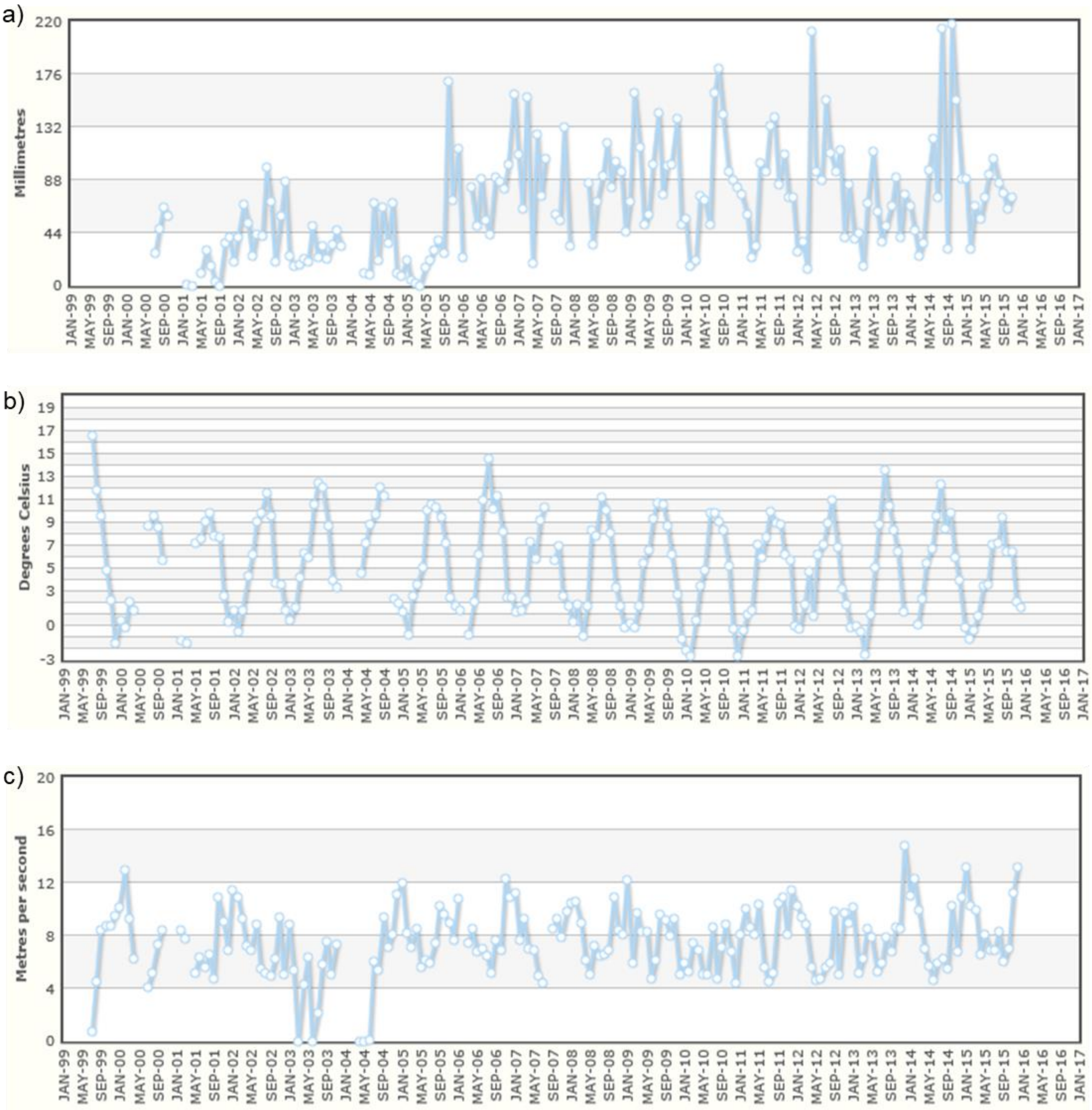


Figure 3-10: Cairngorm (Allt a' Mharcaidh) ECN AWS data

Values for precipitation (a), temperature (b) and wind speed (c) from Jan 1999 to Jan 2017. Derived from hourly data which has been summarised monthly. Source: The ECN Data Centre (2017).

3.6 Conservation

The late Dick Balharry MBE FRSGS, a passionate and well respected conservationist spoke at Glenfeshie in April 2015 after receiving the Geddes Environment Medal about his vision for land use in Scotland (Royal Scottish Geographical Society, 2015). He outlined the benefits of change achieved through an integrated vision, empowerment and recognition of good practice through the use of a formal scheme when it has been achieved. He raised the question of why responsible landowners should be tasked with keeping out damaging deer populations, at substantial private or public cost, while other estate owners are not held liable to keep the deer on their own land.

Balharry’s message was supportive of the work going on at Glenfeshie estate and the idea that it is a conservation success story. He spoke of Glenfeshie estate as working towards a vision of stewardship, inward investment, local employment and with the public interest at heart (whilst maintaining and landscaping hill tracks to benefit the public and the management of the estate). Recognition was also given to the regeneration achieved without fences allowing for the advancement of a natural tree line (Figure 3-11) (Royal Scottish Geographical Society, 2015).

Figure 3-11: Natural regeneration in Glenfeshie

Photos show where the Allt Garbhlach joins the River Feshie on the 12th of August 2014. The new growth of Caledonian pine trees is a result of the sustainable management of the red deer population by Glenfeshie estate.

3.7 Flora on the Mòine Mhór

The modern plant communities of the Cairngorms can be dated back to the retreat of the ice-sheets from the last glacial period about 15,000 years ago (Bennett, 1996). Flora on the Mòine Mhór is associated with the arctic alpine environment of the Scottish upland habitat. The harsh environment of low temperatures, strong winds and a short growing season mean that low-growing vegetation predominately thrives (Wrightham and Kempe, 2006). The growing season for plants drops by about one day for every nine metres of ascent in altitude (Scott, 2016). With the harsh climate, the Mòine Mhór growing season is short and lasts from approximately May until September, though this can be shortened further by late snow and frost in certain locations.

Under my guidance, the Mòine Mhór vegetation was assessed/surveyed by two undergraduate dissertation students in 2014 (Fiona Scott) and 2015 (Michael Delpippo). Furthermore, in 2013, prior to the start of this project, with Olivia Braggs' guidance, Sangita Pandit Karki and Chris Paton surveyed the ground cover and vegetation covering the plateau. Observations relating to the abundance and diversity of the vegetation found on the plateau are presented below. The species noted do not represent the entire flora found on the Mòine Mhór but it does give an indication as to the more commonly observed vegetative cover relating to the study area.

3.7.1 Composition

The arctic-alpine taxon of the Mòine Mhór is high altitude blanket bog, set amongst snow-bed grassland and sedge communities. After snow melt, very rapid shoot growth occurs. The flora is specially adapted to metabolising, reproducing and growing at very low temperatures achieved through having biomass underground or by seed dormancy (Billings and Mooney, 1968). Exposed areas are commonly dominated by dwarf shrubs or woolly fringe moss but in areas where snow is more lasting or where grazing impact has been more severe, grassland can dominate (Wrightham and Kempe, 2006).

Assemblages of vascular plants, bryophytes and lichens that are tolerant to the montane acidic conditions are ones which make the species found in the Mòine Mhór of national conservational interest (Scottish Natural Heritage, 2017b). It was noted that there was variability in species composition on the plateau relating to microtopography, such as slope, aspect, bedrock and water table depth. Springs are where the groundwater emerges from the ground, the water moves over mats of mosses, bryophytes and small vascular plants. The water then seeps away through flushes or sedge mires composed of sedges and other small species which are commonly underlain by mosses or gravel (SNH, 2017).

Vegetation composition in springs and flushes are influenced by the temperature predominantly thriving in cool wet climates and the mineral content of the water. The butterwort indicated base rich soils in the Garbhlach to the acid substrate indicated in the Eidart catchment by the understory of *Sphagnum palustre* and *Sphagnum fallax*. Photographs below show spring and flush habitats at the Eidart (Figure 3-12) and Garbhlach (Figure 3-13) catchments. Characteristic species of springs and flushes were noted across the monitored catchments.

Figure 3-12: Eidart upland plateau vegetation

Bryophyte species including *Sphagnum palustre* and *Sphagnum fallax* are associated with spring and flush vegetation. They are typically found in areas where snow lies late. A common plant in acidic water is the bright green moss *Philonotis fontana* (inset). Photo was taken on 27th of August 2015.

Figure 3-13: Garbhlach upland plateau vegetation

The star-like lime-green leaves of the carnivorous common butterwort (*Pinguicula vulgaris)* stand out against the dark peat (inset). The butterwort is associated with the uplands and has evolved a carnivorous strategy to provide it with enough nutrients. Photo was taken on 30th of July 2015.

A quadrat survey in 2013 of 256 points across the plateau reported that 7 % of the 0.5 x 0.5 m quadrats contained bare peat but that re-vegetation by cotton grass (*Eriophorum angustifolium*) and stiff sedge (*Carex bigelowii*) was common (Bragg *et al.*, 2013). This was supported by findings by Fiona Scott in 2015 who observed the colonisation of common cotton grass in surveyed quadrats (Scott, 2016). This particular grass species is known for its rapid colonisation and can aid the development of *Sphagnum* mosses on areas of bare peat (Mariner *et al.*, 2004).

The 0.5 x 0.5 m dimensioned quadrat survey of 2014 and 2015 covered two catchments and used a belt transect methodology resulting in vegetation data from 80 points, 40 from the Caochan Dubh and 40 from the Eidart catchment. From the count data the most abundant species included *Sphagnum spp.*, cotton grass, mat grass (*Nardus stricta*) and deer grass [sedge] (*Trichophorum* *cespitosum*) (Delpippo, 2015; Scott, 2016b). Bog asphodel (*Narthecium ossifragum*) with its bright yellow flowers has a preference for damp peaty soils and was noted at the Eidart but not at the Caochan Dubh catchment. The large white flowers and orange marmalade berries of the cloudberry were found around the Eidart catchment in the summer of 2015 and 2016 (Figure 3-15). Cup lichens (*Cladonia spp.*) were noted in drier faces and ridges of the plateau. From observations and findings relating to vegetation surveys on the Mòine Mhór, the composition can be described as a mixture of mineral outcrops, woolly-hair moss (*Racomitrium*) heath, mat-grass (*Nardus*) grassland, mire and riparian communities. Photographs over the project timeline of observed flora on the Mòine Mhór are shown in Figure 3-14 and Figure 3-15.

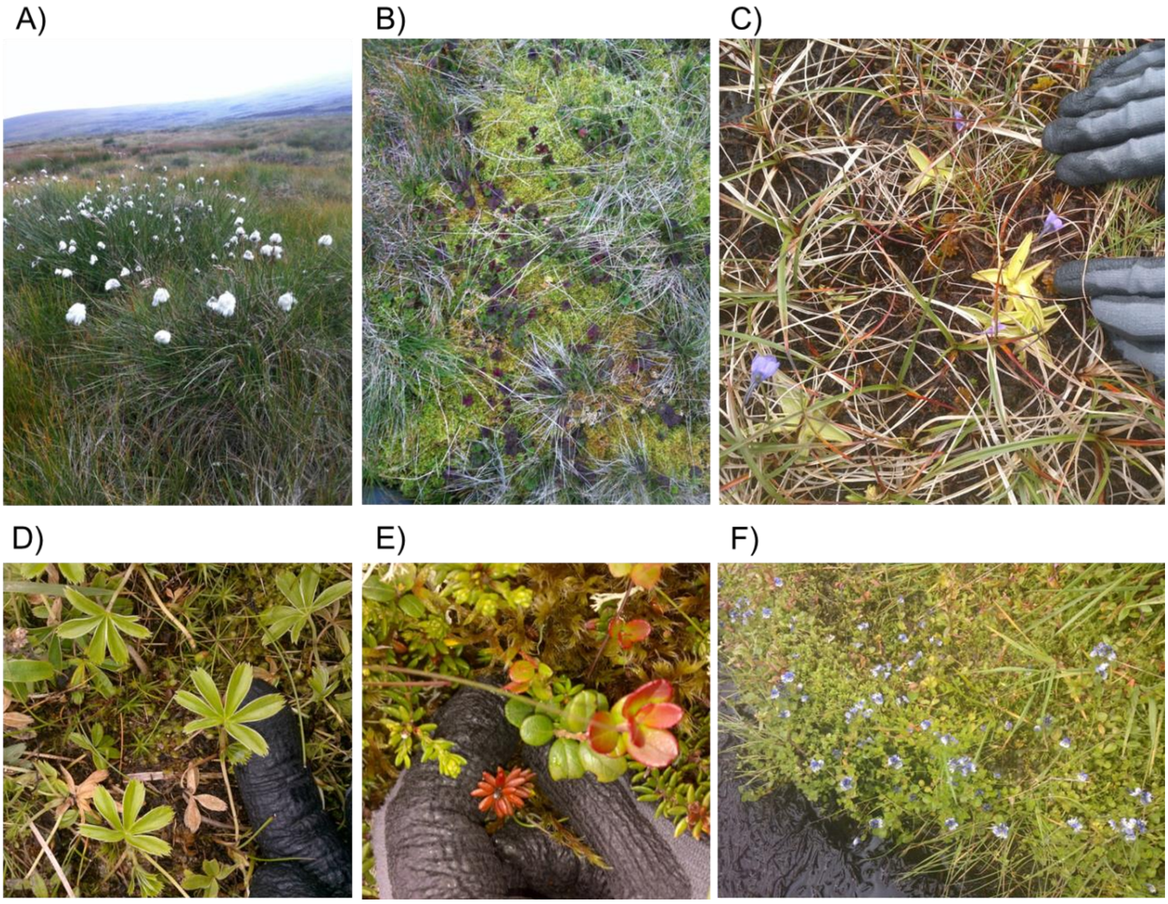


Figure 3-14: Flora on the Mòine Mhór

Hare's tail cotton grass (A), peat moss with the burgundy-leaved cloudberry (*Rubus chamaemorus)* visible (B) and butterwort on a long stalk (~5 cm tall) with a purple flower (C). Bottom row: Leaves of alpine lady's-mantle (*Alchemilla alpina*) (A), the trailing shrub bearberry (*Arctostaphylos uva-ursi*): the leaves turn red in the autumn (E) and the river-bank blue flowering plant is believed to be of the *Veronica* species (F).

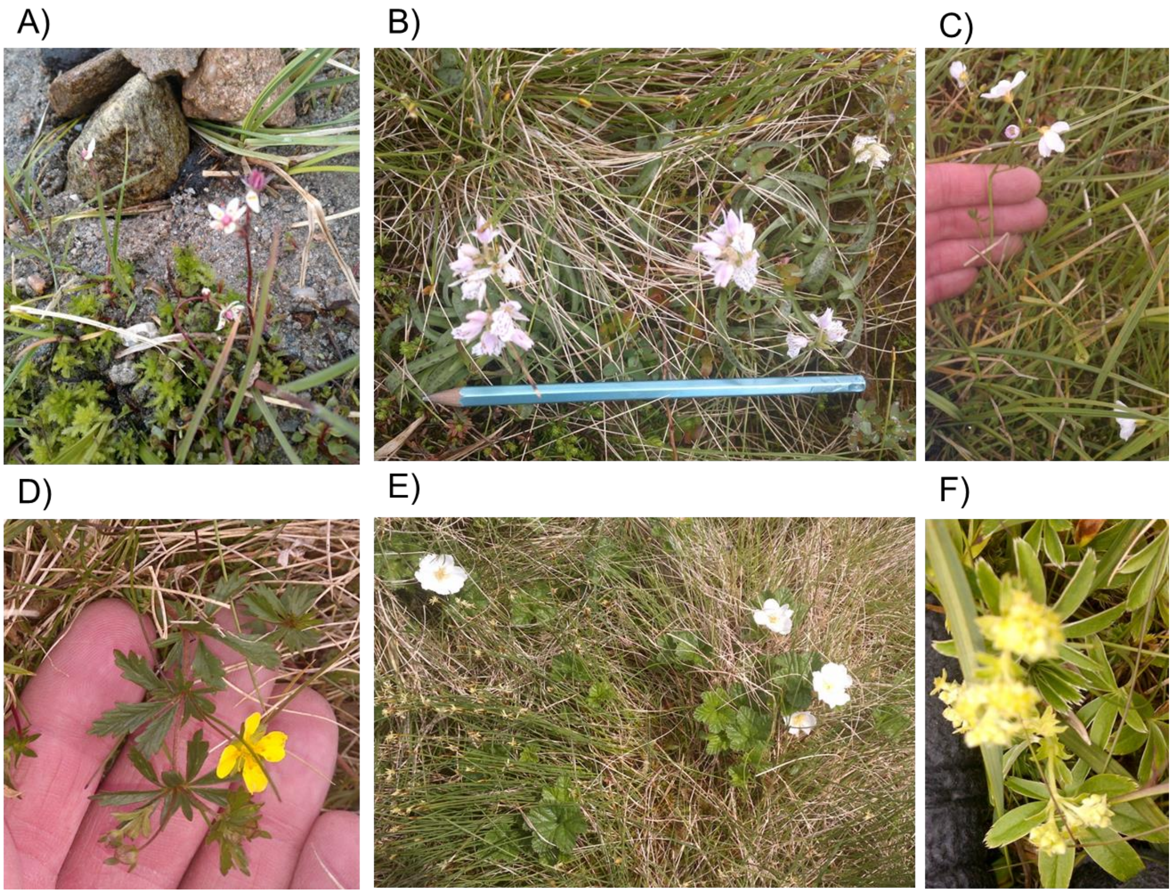


Figure 3-15: Flowering flora on the Mòine Mhór

Stony outcrop with flowering *Saxifraga stellaris* (A), heath spotted-orchid (*Dactylorhiza maculata*) (B) and white flowering Lady's smock (*Cardamine pratensis*) growing in amongst the grass (C). Bottom row: Tormentil (*Potentilla erecta*) has four petals, yellow flowers, and glossy, deeply toothed leaves with three lobes (D), flowering cloudberry (E) and flowering alpine lady's-mantle (*Alchemilla erythropoda*) (F).

Variations in local conditions from the soil moisture, soil temperature, and the amount of sunlight, wind, late-lying snow, water flow and seasonal permafrost influence the arctic-alpine flora. Flora and fauna interact with each other and within the environment itself. The relationship is a mutualistic dependent one; flora provides food and shelter to the fauna. In return fauna can be used to disperse seeds, eat other plant eating animals, pollinate (e.g. bees) or aerate the soil (e.g. worms).

3.8 Fauna within the Mòine Mhór

The fauna observed on the Mòine Mhór are associated with the Scottish upland environment. Visual observations were noted during fieldwork (Appendix B) and the wildlife camera set up on the study site was useful for identifying the presence of fauna on the Mòine Mhór. The fauna identified in this section does not capture all life on the Cairngorms plateau but it does give a representation as to the diversity and specialisation of the wildlife that is well suited and adapted to the artic-alpine environment. The identification of fauna is helpful in understanding the dynamics of grazing and trampling pressures on the study site.

3.8.1 Red deer – *Cervus elaphus*

3.8.1.1 Deer stalking

The sport of deer stalking was first introduced to Glenfeshie around the 1830s when an increase in population size was encouraged for sporting purposes (Scrope, 1839). Additional food was supplied to decrease natural mortality and prevent winter stag emigration (Mitchell and McCowan, 1986). The provision of supplementary feeding still continues throughout Scotland. A questionnaire response from 122 estate/landholdings indicated that 66 respondents (54 %) offered some form of supplementary feeding to deer. Out of the 66 who supplementary feed, the necessity to sustain high deer densities over winter was indicated as a reason in 16 responses (Putman and Staines, 2004). This management tool of winter feeding sustains the surviving population through the winter months impacting on the natural mortality rates and food availability in the landscape during this period.

3.8.1.2 Population management

Annual culling rates at Glenfeshie from 1870 through to the 1990s were commonly 100-120 stags and 60-80 hinds (Grimble, 1901; Whitehead, 1960; Mitchell and McCowan, 1986). Nature conservation interests were then raised due to the damage high deer numbers were thought to be causing to native forest growth and the wider Glen Feshie habitat. The deer cull in 2004 was seen as radical although, since then, the population has continually been managed with positive benefits in nature now becoming apparent. New deer population targets were set and in the 2014/2015 season alone, 1407 deer were culled at Glenfeshie (Thomas MacDonell, personal communication).

3.8.1.3 Mòine Mhór observations

A personal record of red deer observations was noted during study site visits (Table 3-5). It is recognised that this is not representative of the entire population across the project timeline and across the Mòine Mhór however, these observations were useful in indicating the numbers of deer which can be seen on any one occasion. On the 30th September 2015 during benign conditions it was observed that a herd of red deer spent the full day grazing on the Mòine Mhór. An observation of feeding behaviour was that the deer graze on new shoots of cotton grass trying to colonise on areas of bare peat (Thomas MacDonell, personal communication). This hinders re-colonisation of new flora on bare peat as herbivores may graze the vegetation before it has had a chance to establish. Glenfeshie estate is seeking to reverse the degradation which is noted in the SNH condition monitoring reports (Scottish Natural Heritage, 2016e) through natural regeneration as a result of sustained deer population management.

The wildlife camera placement at the spectro::lyser site (tributary of the Caochan Dubh) was the only location to capture images of the red deer. Details of the wildlife camera placements are outlined in Table 3-4. The deer were observed on study site visits elsewhere but the positioning of the cameras at the other two catchment locations across the Mòine Mhór failed to capture any images of the deer (Table 3-5).

Table 3-4: Details of wildlife cameras situated on the Mòine Mhór

Acorn 6210MC HD Wildlife Trail Cameras, Standard Infrared were set to be triggered by motion at locations across the plateau.

Grid Reference	Catchment	Elevation (m AOD)	Date	Duration (months)	Owner
NN 89638 93710	Caochan Dubh	904	Jun 14 – Aug 14	Three	Southampton
NN 91044 95809	Eidart	899	Jul 15 – Feb 16	Eight	Robert Bryder
NN 88725 93213	Garbhlach	957	Oct 15 – Aug 16	Eleven	Olivia Bragg
NN 89638 93710	Caochan Dubh	904	Apr 16 – Aug 16	Five	Robert Bryder

The camera placement at the Eidart faced onto an area of bare peat with the aim of trying to capture an image of herbivores grazing new growth, but this was not observed (Figure 3-16).

Figure 3-16: Outlook of wildlife camera onto an area of bare peat at the Eidart catchment

Deer tracks were evident following the course of the river on the east side of the Eidart stream. This may have proved a more successful location to capture images of the herbivores although the positioning of the camera facing an area of bare peat served a purpose in itself.

Figure 3-17: Red deer on the Mòine Mhór

Pictures of red deer hinds and fawns captured on motion camera (June, July and August of 2014 and 2016) whilst positioned at the spectro::lyser site within the Caochan Dubh catchment.

Table 3-5: Field notebook observations of red deer on the Mòine Mhór

During study site visits a note was kept of any deer observed on the plateau (Note CD is the Caochan Dubh catchment).

Date & Time (GMT)	Hinds	Stags	Total Number	Catchment
11/09/2014 07:45			100+	CD and Eidart
24/09/2014 11:15			12+	CD and Eidart
09/10/2014 13:30	1	2	15+	Garbhlach
10/10/2014 10:30		3		CD and Garbhlach
26/10/2014 10:30			60+	CD
28/11/2014 11:05	1			CD
27/08/2015 09:40	1 + calf			Eidart
01/09/2015 09:25	1	1		CD
09/09/2015 09:10			35+	CD
30/09/2015 08:30			100+	CD

Deer tracks were observed while traversing off the main access track to visit the eight monitoring stations. Well established deer tracks were visible across the plateau and on every visit (when the study site was not snow covered). Deer scat and deer hoof prints were noted even if deer were not physically seen; the evidence they had been there was apparent. As well as utilising deer paths the herbivores would also wander over areas of bare peat (Figure 3-18).

Figure 3-18: Hoof prints on the Mòine Mhór

The hoof prints have been highlighted for the ease of the reader by white outline. Photographs of herbivores trampling over bare peat areas were taken in August 2015.

3.8.1.4 Mòine Mhór movements of deer

In the winter, once the study site was snow covered, it is known that the deer move to lower grounds for shelter and food. The deer move down to the forest which is of concern for the natural regeneration of woodland in Glen Feshie. An example of this was observed on 31st January 2016 15:00 GMT when a few hundred deer were observed grazing at the Pass of Drumochter (40 km south of Glen Feshie). It was easy to pick out the brown/grey coats against the snow covered ground; they were grazing all over the open land of the hill. This is not an uncommon sight in the winter months as deer can spend most of their day foraging.

3.8.2 Reindeer - *Rangifer tarandus*

The Cairngorm Reindeer are a free-ranging herd of around 150 reindeer, most ranging on the Cairngorm Mountains with the rest located on Glenlivet estate (Cairngorm Reindeer, 2017). The mature males (bulls) are solitary during the summer months whereas the female and young form herds (The Reindeer Company, 1993). Reindeer are known as gregarious (sociable) animals and four females (cows) and one calf were spotted on the 15th July 2015 18:00 GMT at the Eidart catchment. Calves of domestic reindeer herds are generally born within one month of each other around the months of May to June (Lent, 1965). The reindeer were observed on the north side of the river and their coats were a brown/grey colour. The wildlife camera situated at the Eidart catchment during this period captured a picture of what is believed to be reindeer antlers on the 19th July 2015 03:39 LT (Figure 3-19).

Figure 3-19: Reindeer antlers on the Mòine Mhór

Infrared image captured on wildlife camera whilst positioned at the Eidart catchment (note what is believed to be the antlers of a Cairngorm reindeer on the right-hand side of the image). A thick velvet skin protects the antlers while they grow. Once grown, the velvet is shed and the solid bone is exposed (antlers are shed on a yearly basis).

Reindeer were reintroduced to the Cairngorms National Park in 1952 (Gilbert, 1974; Cairngorm Reindeer, 2017). The conditions in the Cairngorms are able to support the animals; they feed selectively on lichen and arctic vegetation (grasses, sedges, heather and blaeberry) with a preference for mushrooms (The Reindeer Company, 1993). It has been estimated that a reindeer needs around four pounds of moist lichen daily (Gilbert, 1974). Their widely splayed, broad, flat and deeply cleft hooves allow them to move around on soft snow without sinking. They differ from other members of the deer family in that both sexes normally develop antlers (Lent, 1965). As with the red deer, large areas of grazing pasture are required to prevent over-grazing and trampling. The reindeer's preference for terricolous lichen may differ from the red deer's primary choice in diet (Utsi, 1957). A quantitative measurement of the damage caused by 500 reindeer in Alaska concluded that where lichens are an important part of foraging, if lichens represent 30 % of the available forage then around 15 % should be considered unavailable due to trampling impacts (Pegau, 1970). The Cairngorm herd have access to a plentiful supply of over 7,000 acres of free-range grazing (Cairngorm Reindeer, 2017).

3.8.3 Mountain hare - *Lepus timidus*

Other fauna includes the mountain hare which is indigenous to Britain. The mountain hare's diet consists of heather (particularly *Calluna vulgaris*), grasses, rush and sedge species. The mountain hare is an arctic/subarctic/alpine species which is found chiefly in the central and eastern Highlands of Scotland, connected to the heather moorland managed for red grouse production (Newey *et al.*, 2007). A study by Watson and colleagues in 1973 found that hare density can surpass 200 km^2 in managed moorland (predator control and rotational burning primarily for grouse) compared to 0.5 – 3 km^2 outwith these areas (Watson *et al.*, 1973). The presence of the mountain hare was noted on many study site visits despite their reputation as solitary and timid creatures. The wildlife camera placement at the spectro::lyser and Eidart locations captured a few images of curious hares (Figure 3-20). A buried pile of hare pellets was also seen on a snowy winter's day on the Mòine Mhór when walking to the Caochan Dubh catchment.

On the 6th of May 2016, three young hares were observed at 08:00 GMT on the plateau and another inquisitive hare was seen at 14:20 GMT at the Garbhlach catchment. Mountain hares start breeding in late February and with a 50 day gestation period females can have up to three litters (5-6 young total) in a year (Flux, 1970; Hewson, 1976; Iason, 1990). Hares are normally nocturnal (as confirmed by night-time images captured on the wildlife camera) but in the winter are forced to look for food during the day. Hares were always observed on the move or on the lookout rather than eating.

Figure 3-20: Mountain hare on the Mòine Mhór

Infrared images captured of the mountain hare during the night/early hours of the morning. Note the seasonal change in plumage as related to climate (Watson, 1963) from dappled brown to white plumage, helping to keep them camouflaged from predators in the snow.

The home range size of mountain hares in Scotland was found to correlate with food availability and the mean annual estimate was 64 ha for males and 62 ha for females (Hewson and Hinge, 1990; Hulbert *et al.*, 1996). Predators of the mountain hare include golden eagles, foxes and stoats (Newey *et al.*, 2007). Lack of snow cover whilst in their winter plumage heightens the risk of predation as has been the case in winter 2016/17 in the Cairngorms (Raynor, 2017). Mountain hares have suffered from a decline in numbers as a result of habitat loss, fragmentation and local over-exploitation (Newey *et al.*, 2008). The conservation and sustainable management of mountain hares is protected under Annex V of the EC Habitats Directive, 1992. Long-term global climate change is likely to impact negatively on the higher montane/arctic habitat suitable for mountain hares and other species such as upland birds (Newey *et al.*, 2008).

3.8.4 Upland birds

Although there is no agreed definition or list of upland birds, some birds signify an association with the open ground conditions usually found at higher altitudes (Ratcliffe, 1977b, 1990). The specific montane species that live above the tree-line include the ptarmigan (*Lagopus muta*), dotterel (*Charadrius morinellus*) and snow bunting (*Plectrophenax nivalis*) (Ratcliffe, 1990). In the 1990s these Cairngorm breeding birds were extensively studied (Thompson and Brown, 1992; Galbraith *et al.*, 1993; Owens *et al.*, 1994; Rae, 1994; Smith, 1994; Thompson *et al.*, 1996). The upland avifauna distribution and abundance is driven by food supply and the availability of appropriate nesting habitat (Ratcliffe, 1977b).

It has been suggested that Glenfeshie is one of the best performing habitats for black grouse *(Tetrao tetrix)* in the UK (Thomas MacDonell, personal communication). Immediately after crossing the River Feshie *en route* to the Mòine Mhór, black grouse were observed gathered on an area of open and flat ground taking part in a behaviour known as lekking (courtship displays). This was noted on a number of occasions throughout the year and took place at around sunrise. Red deer grazing can have adverse impacts on availability of black grouse habitat for nesting (tall dense heather) and for feeding (rich wet flushes, grasses and *Sphagnum* mosses) (Roos *et al.*, 2016). Overgrazing can also impact on the proportion and height of *Vaccinium spp.* and the linked amount of lepidopteran larval prey available for chicks (Baines, 1991; Baines *et al.*, 1994).

The capercaillie *(Tetrao urogallus)* is also suited to the naturally re-generating Caledonian pine forests of Glen Feshie. Other members of the grouse family, ptarmigan *(Lagopus mutus)* and red grouse *(Lagopus lagopus)* are also suited to the higher ground of the Mòine Mhór. Red grouse and black grouse were captured on the wildlife camera situated at the spectro::lyser site (Figure 3-21). The spectro::lyser required a power source and a stand was built to house this which may have attracted more animals to come over and explore, possibly contributing to the diversity of images captured when the camera was placed here. As the stand was elevated off the ground to keep the batteries safe and out of the snow, one could imagine that the underneath of the stand could provide a shelter for curious passers-by. This hypothesis was confirmed by frequently finding droppings under (or on) the stand when visiting the spectro::lyser site.

Figure 3-21: Game birds on the Mòine Mhór

Images of red grouse (a, b & c) and a black grouse (d) captured on the wildlife camera.

One particular bird that was observed on a regular basis on field visits was the golden plover *(Pluvialis apricaria)*. After spending the winter elsewhere, the golden plover should make an early return to the moors and hills before the end of February in a mild season (Ratcliffe, 1977b). The golden plover was low flying and appeared protective of its breeding ground. The call of the golden plover was also a very distinctive noise.

The natural regeneration appears to be having a positive impact with regards to the avifauna population however the changing climate and distinction between seasonal timings can impact on the vulnerability of the upland birds to predators such as the fox.

3.8.5 Fox – *Vulpes vulpes*

The fox can be found throughout the UK across all environments from mountains through to urban areas. Foxes are omnivorous and can eat a wide range of food including mice, voles, rabbits, lambs and berries. They also prey on birds such as grouse, ptarmigan, curlew and the golden plover. An infrared image of a fox was captured on the motion camera on the 7th March 2016 at 20:12 GMT, the temperature was recorded at -9 °C (Figure 3-22).

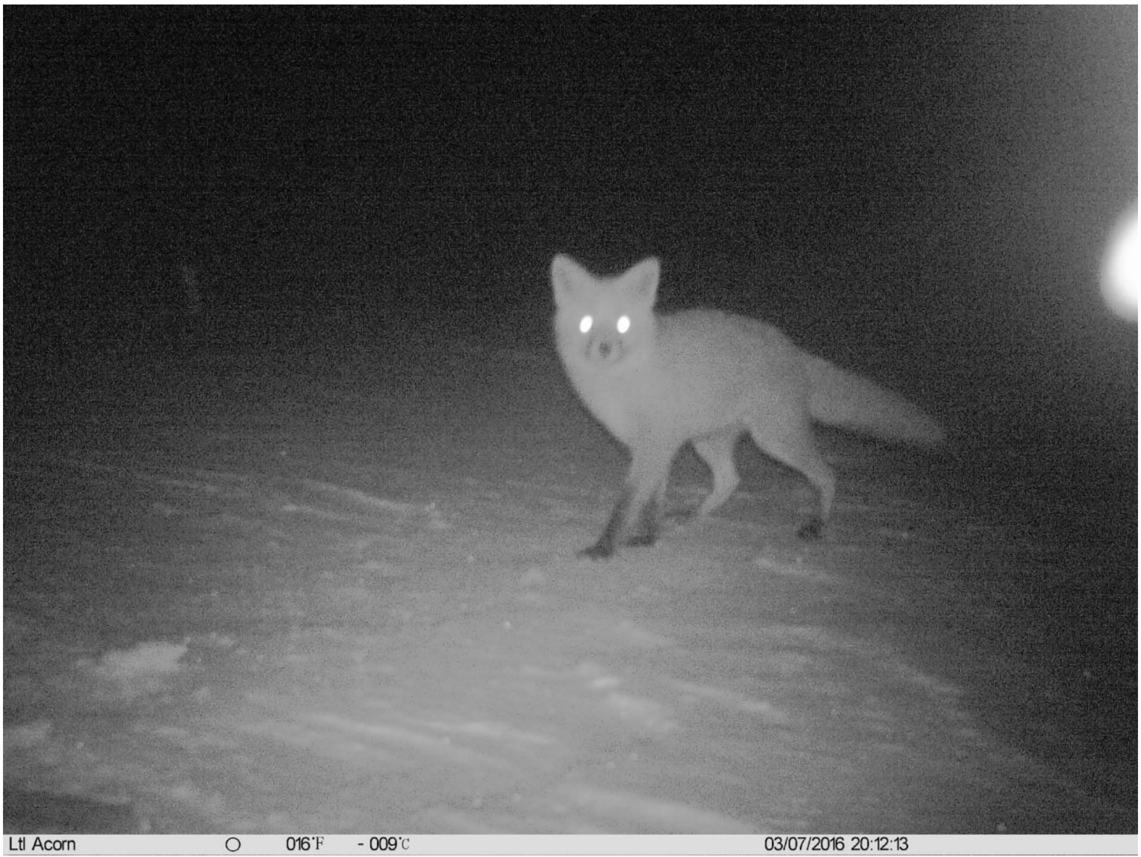


Figure 3-22: Red fox on the Mòine Mhór

The red fox is the largest member of the *Vulpes* genus with variations in size dictated by food and territory availability. Foxes found in the Scottish uplands can be larger than the rest of the UK if there is a plentiful supply of food and available territory.

3.9 Summary

The flora and fauna of the Mòine Mhór are reflective of the high-altitude upland environment upon which it is located. Specialised species that are suited to the peatland habitat are found on the plateau. The flora have adapted to the short growing season and arctic-alpine environment of the Mòine Mhór. This in turn provides a food source and habitat for the fauna which are observed on the plateau, including deer, hare, upland birds, foxes, insects and others. These conditions are pivotal to the survival and success of the biodiversity found on the study site.

Following on from the study site characterisation are the specific data collection methods used in relation to this particular project on the Mòine Mhór upland peatland, situated within Glenfeshie estate grounds.

4. Materials and methods

4.1 Overview

To achieve the project aim(s), aquatic carbon loss was monitored at eight streams draining the study site (Table 4-1) using a combination of field and laboratory based analysis (Table 4-2). The Mòine Mhór is described as an actively eroding upland blanket bog that has a variety of specialised flora and fauna that are adapted to the arctic/alpine environment. The Mòine Mhór was divided into eight drainage catchments, of these; four catchments were nested, Caochan Dubh upper (CD U), Caochan Dubh north east (CD NE), Caochan Dubh north west (CD NW) and Mòine Mhór south east tributary (MM SE T); all nested within Caochan Dubh lower (CD L). All these, and also the Eidart upper drained into the River Feshie via the River Eidart. Two further sites drain west into the River Feshie, the Garbhlach east (Gar E) and the Garbhlach north east (Gar NE). The River Eidart is the main tributary of the River Feshie. A summary of the study catchment characteristics is presented below in Table 4-1.

Table 4-1: Summary of study catchment characteristics

Note that CD L is a nested catchment with water draining from MM SE T, CD U, CD NW and CD NE. Maximum and minimum elevations of catchment areas interpreted from contour data viewed in QGIS. The minimum and maximum range in slope was calculated from slope angle map (Figure 3-3) clipped to catchment areas in QGIS. Percentage of bare peat is taken from Figure 3-7. Mean annual water temperatures are shown for the year 2014 as this represents a complete data set (365 days data across all monitored streams). Altitudinal range refers to the height range within the specified catchment area. Mean flow is calculated from the daily flow data largely covering from Nov 2013 – Sep 2016; apart from at monitoring stream CD NE where there was a lack of confidence in the accuracy of the results captured.

Stream	Grid Reference	Catchment area (km^2)	Min elevation (m AOD)	Max elevation (m AOD)	Range in slope (^{o})	% bare peat	Stream order	Channel width at gauging point (m)	No. gaugings	No. sampling occasions	Mean annual water temperature (^oC)	Mean flow ($m^3\ s^{-1}$)
CD L	NN 90259 93999	4.61	890	1020	0-31	34	3rd	4.20	8	18	4.75	0.281
CD NE	NN 89819 94583	0.24	910	940	0-12	38	1st	0.90	7	23	4.80	-
CD NW	NN 89842 94771	0.21	910	950	0-9	35	1st	0.50	6	20	4.85	0.003
CD U	NN 89648 94654	2.30	910	1020	0-28	42	2nd	2.90	7	25	4.91	0.086
Eidart U	NN 91116 95844	1.61	890	1052	0-24	27	2nd	4.20	9	17	4.77	0.158
Gar E	NN 88935 94166	1.10	920	1010	0-19	26	2nd	1.15	7	25	4.72	0.095
Gar NE	NN 88778 94741	0.18	920	940	0-38	16	1st	1.00	7	21	4.61	0.029
MM SE T	NN 89638 93710	1.14	910	980	0-20	30	2nd	2.80	11	42	4.82	0.103

This chapter reports on field methods used that relate to understanding the current condition of the study site followed by the analysis undertaken upon return to the laboratory (Table 4-2).

Table 4-2: Summary of the main variables measured and methods used

Grouping	Variable	Field Method	Laboratory Method
Level, temperature and flow data	Stage height	HOBO data logger/stage board	-
	Flow	Flow gauging	-
Water chemistry	Stream pH and temperature	Hanna handheld meter	pH probe
	Stream conductivity	Hanna handheld meter	Cond. probe
	Dissolved oxygen	-	DO probe
	Water turbidity/absorbance	Water sample	Colorimeter
	DOC, TC & DIC	Water sample	TOC analyser
	Suspended sediment	Water sample	Filtration
	Turbidity, nitrate, TOC, DOC & colour	Spectro::lyser	-
Weather data	Precipitation	Storage gauge/ weather stations	-
Inorganic carbon	Dissolved CO_2	DIC probe/ headspace sampling	Gas chromatography
Erosion	Loose peat blocks	Survey of bank to quantify blocks	-

4.2 Equipment and software

The materials used to achieve the project aim(s) have been summarised in Table 4-3 and are inclusive of the field, laboratory and desk work phases associated with the project.

Table 4-3: Computer software packages and equipment used in this study

Supplier	Package	Purpose
Autodesk	AUTOCAD 2010	Catchment size calculations
Edina	Digimap	Mapping
Elsevier	Mendeley Desktop	Reference manager
Enterprise Content Management	Prism Software	Graphing and statistics
Golden Software	SURFER v10	3D surface
Institute of Hydrology	HYDATA 4.2	Creation of rating curves
CSIRO Australia / CEH	IHACRES	Comparison rainfall-runoff model
Microsoft Corporation	Microsoft Office 2010	Writing, analysing and presenting data
Onset	HOBOware Pro Software Version 3.7.5	Communication with logger
QGIS Development Team	QGIS	Mapping
S::can	Ana::Pro Software Version 5.9g	Communication with spectro::lyser
Vaisala	M170 Link Software Version 1.16	Communication with USB cable, for MI70 indicators
Supplier	**Equipment**	**Purpose**
-	Spectrophotometer	Measure absorbance
Garmin	Handheld GPS	Navigation
Hanna Instruments	HI 98140 pH meter	Measure pH
Hanna Instruments	HI 9033 multi-range conductivity meter	Measure conductivity
Hanna Instruments	HI 9143 microprocessor dissolved oxygen meter	Measure dissolved oxygen
ISCO	6712 Full-Size Portable Sampler	Monitor water quality
Ltl Acorn	6210MC HD Wildlife Trail Cameras, Standard Infrared	Monitoring fauna
NUMAX	2 x Leisure Battery 12v-110Ah Numax CXVX31MF	Power requirement
Onset	HOBO Water Level Logger	Monitor water level and temperature
Ott	C-2 Current Meter	Flow gauging
Ott	MF Pro	Flow gauging
S::can Messtechnik GmbH, Austria	Spectro::lyser	Monitor water quality
Shimadzu	LabTOC	Measure DOC
Solar Technology	2 x 17.5v 2.64A PV Logic STP043 43W Solar Panels	Power requirement
Vaisala	Dissolved Inorganic Carbon Probe	Monitor inorganic carbon
Whatman	Microfiber filter papers (diameter 47 mm, pore size 0.7 micron)	Filtering samples

4.3 Water level and temperature

4.3.1 HOBO® logger location

The hydrological aspects of the data collection included the collection of water level and temperature data. Eight gauging locations were monitored on the study site (Table 4-4). This number was chosen to cover all the streams draining from the Mòine Mhór plateau. The eight streams sampled are the CD L, CD NE, CD NW, CD U, Eidart U, Gar E, Gar NE and MM SE T (Table 4-4). For ease, when reporting results (e.g. graphing) the shortened names (location ID) have been used. These names have been derived from the actual stream name itself or where applicable, the direction the source of the catchment comes from.

Table 4-4: Sampling locations of the monitored streams used in the study

The grid references highlight the location where water samples were collected, water levels were recorded and where flow gauging was carried out.

Location	Location ID	Grid Reference
Caochan Dubh lower	CD L	NN 90259 93999
Caochan Dubh north east tributary	CD NE	NN 89819 94583
Caochan Dubh north west tributary	CD NW	NN 89842 94771
Caochan Dubh upper	CD U	NN 89648 94654
Eidart upper	Eidart U	NN 91116 95844
Garbhlach east	Gar E	NN 88935 94166
Garbhlach north east	Gar NE	NN 88778 94741
Mòine Mhór south east tributary	MM SE T	NN 89638 93710

4.3.2 HOBO® logger set-up

In order to effectively manage water resources, water level is monitored in order to calculate flow. To obtain water level data, HOBO loggers were deployed at the Mòine Mhór study streams. The HOBO water level loggers were cable tied to a piece of angle iron which was fixed into the river bank. At each of the gauging locations, a HOBO logger was installed which recorded absolute pressure in kilo-Pascals (kPa) and temperature in degrees Celsius (°C) at 15-minute intervals. The logger was set to stop logging when full, which gave 228 days storage capacity.

4.3.3 HOBO® logger deployment

Deployment location within the stream was taken into consideration in order to optimise the data quality gathered from the loggers. The selection criteria for suitably siting the HOBO loggers in the eight monitored catchment areas (Table 4-4) were as follows:

- An area in which the logger would remain securely mounted;
- had good water mixing;
- where the sensor would be submerged at all times; and
- HOBO logger located sufficiently deep but not touching the river bed.

4.3.4 Barometric logger

In addition to the eight HOBOs deployed at the monitored streams to record water pressure and temperature, an additional HOBO logger, referred to as a barometric logger was deployed to record the ambient air pressure and ambient air temperature. Raw data on pressure was converted into a value for water level using pressure data gathered from a barometric compensation data logger situated at Feshiebridge in a hut primarily used by SEPA to monitor level on the River Feshie. Initially, atmospheric pressure was taken from the Feshiebridge atmospheric HOBO (232 m above ordnance datum (AOD)), which was then replaced with a high altitude barometric HOBO (placed on the Mòine Mhór at 914 m AOD). The high altitude barometric HOBO was deployed in August 2014 and was used in place of the low altitude barometric HOBO thereafter. Mounting considerations for the barometric logger included locating in a shaded area where temperature variations were minimised. The distance of the barometric logger to the HOBO logger should be as small as is manageable with a focus on positioning it at a similar altitude; this was also taken into consideration hence the move from Feshiebridge (~7 miles but significantly lower in altitude) to the Mòine Mhór (onsite).

4.3.5 Converting pressure to level

Absolute pressure was measured in kilopascal (kPa), the SI derived unit of pressure. Post-processing of the data utilised the HOBOware Barometric Compensation Assistant. Water level (m) over time was calculated by the following equation:

$$= (\text{Stream absolute pressure - Atmospheric absolute pressure}) * 0.10197$$

Equation 4-1: Water level calculation

The multiplication value of 0.10197 is used to convert kPa of pressure to metres since the length of a column of water exerting 1 kPa of pressure is 0.10197 m (Fluck, 1992). The derived level data was combined in one Excel spreadsheet to allow for comparisons between monitored catchments.

4.4 Interpolation of missing Mòine Mhór barometer data

The HOBO used to record air pressure and temperature on the Mòine Mhór was not installed until the 29th of August 2014 and also had a period of missing data between the 28th of November 2014 and the 5th of December 2014. Various methods were investigated for deriving the high altitude Mòine Mhór air pressure for the study period where no observed data existed by use of the observed barometric data from the Feshiebridge location and also by use of observed stream temperature at the site.

As mentioned in Section 4.3.4, initially atmospheric pressure was taken from a HOBO located at Feshiebridge (232 m AOD) and in August 2014 atmospheric pressure was taken from a new HOBO located on the Mòine Mhór plateau at 914 m above ordnance datum (AOD). Of note is the difference in location and elevation of the HOBOs recording ambient air pressure across the duration of the study. This meant that the earlier data (Nov 2013 to Apr 2014 plus any periods of missing data in the Mòine Mhór pressure) required a correction applied to the atmospheric pressure to take account of these altitudinal differences. Due to humidity, temperature and density altitudinal differences, it was decided that a simple calculation involving the height differences was not the best way forward. For this reason, where an overlap of data existed, the relationship between the low altitude and high altitude barometric unit was explored. The two main methods used to derive Mòine Mhór atmospheric pressure prior to installation of the Mòine Mhór atmospheric HOBO are discussed below.

Method 1: Use Feshiebridge observed barometric pressure plus local water temperature to predict air pressure at Mòine Mhór by use of a formula derived from a regression analysis of observed air pressure for the data logged after installation of the Mòine Mhór HOBO versus Feshiebridge observed air pressure and Mòine Mhór stream temperature. Temperature affects air density and humidity and as such can be expected to have a very strong relationship with observed air pressure.

In order to choose which stream temperature to use, a Pearson correlation matrix was used to determine the associations of stream temperature between the monitored streams. From Table 4-5 it can be seen that the Garbhlach east site had a strong association with the other monitored streams. All the values are close to +1, which indicates a strong positive association between the two variables (stream temperature).

Table 4-5: Stream temperature (˚C) correlation matrix

Data from 29 Aug 2014 to 30 Sep 2016. The PEARSONS function in Excel reflects the extent of a linear relationship between two data sets.

	MM SE T	Gar NE	Gar E	Eidart U	CD U	CD NW	CD NE	CD L
MM SE T	X	0.949	0.987	0.988	0.979	0.990	0.980	0.981
Gar NE		X	0.964	0.969	0.951	0.948	0.986	0.972
Gar E			X	0.988	0.983	0.986	0.986	0.982
Eidart U				X	0.987	0.990	0.992	0.992
CD U					X	0.980	0.975	0.981
CD NW						X	0.993	0.982
CD NE							X	0.986
CD L								X

Having chosen Garbhlach east as a representative stream temperature source to use a regression analysis between observed pressure from the Mòine Mhór barometric HOBO, observed pressure from the Feshiebridge HOBO and Garbhlach east stream temperature was carried out for the period of maximum overlapping data, 05/12/2014 – 13/04/2016. This gave a formula defining the relationship between the variables with an associated r^2 value of 92.2 %. This indicates that the estimated values for Mòine Mhór pressure are 92.2 % explained by the use of low altitude (Feshiebridge) pressure and Mòine Mhór stream temperature. As a validation test of the regression equation and to eliminate seasonal bias, the regression was then carried out on one full year of Garbhlach east temperature data (2015) versus observed Mòine Mhór barometric logger data. This gave a more robust r^2 value of 96.5 % which indicates a good fit between observed Mòine Mhór barometric pressure and estimated Mòine Mhór pressure from Feshiebridge pressure and Garbhlach east temperature from the regression outputs. The Excel equation used to estimate Mòine Mhór pressure using Feshiebridge pressure and Garbhlach east temperature observations for 2015 was as follows:

*= IF (Mòine Mhór Pressure > 1, Mòine Mhór, (-1.29477 + (0.931365 * Feshiebridge Pressure) + (0.057851 * Gar E Temp)))*

Note that the first part of the formula simply ensures that observed Mòine Mhór pressure will be used where it has been logged.

Equation 4-2: Barometric pressure calculation (kPa)

Method 2: Use the Barometric Formula to estimate the air pressure at the Mòine Mhór location from observed air pressure values at Feshiebridge along with the predicted temperature drop between Feshiebridge (FB) and Mòine Mhór (MM) altitudes.

The Barometric formula, sometimes also known as exponential atmosphere or isothermal atmosphere, is used to compute air pressure at a given altitude from the known pressure at a base level. The formula is based on a mathematical model of the Earth's atmosphere and takes into account the temperature lapse rate (drop in temperature as altitude increases). The Barometric formula is as follows:

$$P = P_b \left[\frac{T_b}{T_b + L_b \cdot (h - h_b)} \right]^{\frac{g_0 \cdot M}{R^* \cdot L_b}}$$

Where:

P = Pressure (Pa)
P_b = Pressure (Pa) at base level
T_b = Standard Temperature (K)
L_b = Standard Temperature Lapse Rate (K/m) in ISA
h = Height above sea level (m)
h_b = Height at bottom of layer b
R^* = Universal gas constant: 8.3144598 J/(mol·K)
g_0 = Gravitational acceleration: 9.80665 m/s^2
M = Molar mass of Earth's air: 0.0289644 kg/mol
Units: Pa (Pascal), K (Kelvin), m (metre), J (Joule), mol (mole), s (second), kg (kilogram)

Equation 4-3: Barometric formula

If the known Feshiebridge barometric pressure is taken as the base level then the Barometric Formula can be used to calculate the expected air pressure at the Mòine Mhór altitude. The formula can be simplified by substituting known values for the study site as follows:

Lapse Rate L_b (change in temperature with altitude) = Standard temperature lapse rate in ISA layer 0-11,000m is -0.0065 K/m for dry air.

Observed Lapse Rate at site; Mean temperature drop from FB Hobo location to MM Hobo location (calculated for maximum data overlap period 29/8/14 15:00 to 13/4/16 16:45 UTC) = 5.63 °C. Lapse Rate = -(dT/dz) where dT is change in temperature and dz is change in altitude.
Observed Lapse Rate = -(-5.63 / 682) = -8.258694 °C/km = -0.008259 °C/m
= -0.008259 K/m (units of Kelvin and Celsius are the same)

h = 914m (height of MM Site AOD)

h_b = 232m (height of FB Site AOD)
This simplifies the formula to:

$P = P_b (T_b / T_b + 4.433)$ ^5.2558 *using temperature lapse rate for ISA (0-11,000m)*

$P = P_b (T_b / T_b + 5.633)$ ^4.1364 *using observed lapse rate between FB and MM*

Where;

P = Barometric pressure at MM site (Pascals)

P_b = Barometric pressure at FB site (Pascals)

T_b = Temperature at FB site (Kelvin)

Equation 4-4: Mòine Mhór Barometric formula

4.4.1 Analysis and comparison of results using different methods

The Mòine Mhór air pressure was calculated using the two methods detailed above and various variations of the Barometric formula method, results were then compared to observed data during overlap periods to find the most accurate method for predicting Mòine Mhór air pressure during period of missing data. The methods used were as follows:

Method 1: Use FB observed barometric pressure plus local water temperature to predict air pressure at Mòine Mhór by use of a formula derived from a regression analysis of observed air pressure for the data logged after installation of the Mòine Mhór HOBO versus Feshiebridge observed air pressure and Mòine Mhór stream temperature (Method 1 above).

P = (-1.29477 + (0.931365 * Feshiebridge Pressure) + (0.057851 * Gar E Temp))

Method 2a: Use Barometric formula with standard temperature lapse rate of -0.0065 K/m (Method 2 above).

$P = P_b (T_b / T_b + 4.433)$ ^5.2558

Method 2b: Use Barometric formula with observed temperature lapse rate of -0.008259 K/m (variation of Method 2a using observed temperature lapse rate between Feshiebridge and Mòine Mhór from mean of logged temperatures during overlap period).

$P = P_b (T_b / T_b + 5.633)$ ^4.1364

Method 2c: Use Barometric formula with observed temperature lapse rate and -0.101 kPa offset applied which was equal to the mean of the difference between calculated and observed values during the overlap period (variation of Method 2b to account for constant errors in the Barometric formula caused by effects of topography and moisture levels - Barometric formula is based on a uniform standard atmosphere model and dry air and gave a calculated result that was 0.101 kPa higher than observed during overlap period).

$P = (P_b\ (T_b / T_b + 5.633)\ \hat{}4.1364) - 0.101$

As with Method 1, regression analysis between the calculated Mòine Mhór barometric values and observed values through overlap periods 05/12/2014 14:30 to 13/04/2016 16:45 (maximum period available) and also 01/01/2015 00:00 to 31/12/2015 23:45 (one calendar year) were carried out. The results showed a closer relationship for the one year period (r^2 value of 97.4) than the maximum overlap period (r^2 value of 95.0). This might be expected due to seasonal bias so further comparisons were done using overlapping data from 2015 rather than the maximum available period.

Calculated Mòine Mhór pressure using the four methods and variations detailed above was compared to the observed Mòine Mhór pressure values to indicate which method would give the best correlation and thus be used to calculate Mòine Mhór pressure for the period of missing data. Analysis was done by populating a Correlation matrix in Excel and the correlation coefficient values were all very high (>0.9).

Further analysis was done on the methods and variations used by performing a regression analysis between MM Observed Pressure against the various calculated values for the period of 2015. Table 4-6 below summarises the outputs of the regression analysis for the four methods / variations.

Table 4-6: Regression Analysis of observed MM pressure against calculated, 2015

Regression Statistic	**Method 1** MM Baro - FB P, GarE T regression 2015:	**Method 2a** MM Baro from Barometric Formula using standard lapse rate:	**Method 2b** MM Baro from Barometric Formula with obs. temp. lapse rate:	**Method 2c** MM Baro from Baro Formula with obs. temp. lapse rate + fixed correction:
Multiple R	0.981	0.987	0.987	0.987
R Square	0.962	**0.974**	0.974	0.974
Adjusted R Square	0.962	0.974	0.974	0.974
Standard Error	0.233	0.193	0.193	0.193
Number of Observations	35039	35039	35039	35039

The regression summary above gives an indication of how closely the calculated values for MM Barometric Pressure follow the observed values during the period 2015. An r square value close to 1 indicates that values follow well. The r square values are all very close to 1, Method 2a MM Baro from Barometric Formula using standard Lapse rate indicates the best correlation with MM Baro observed values.

Further analysis was done on the methods and variations by performing summary statistics on the differences between calculated and observed values. Table 4-7 below summarises the results.

Table 4-7: Analysis of difference between observed MM pressure and calculated, 2015

Statistic	**Method 1:** MM Baro Obs - MM Baro - FB P, GarE T regression 2015:	**Method 2a:** MM Baro Obs - MM Baro from Barometric Formula using standard lapse rate:	**Method 2b:** MM Baro Obs - MM Baro from Barometric Formula with obs. temp. lapse rate:	**Method 2c:** MM Baro Obs - MM Baro from Baro Formula with obs. temp. lapse rate + fixed correction:
Standard Deviation	0.233	**0.194**	**0.194**	**0.194**
Mean	0.010	-0.085	-0.101	**0.000**
Minimum	-2.720	-2.791	-2.808	-2.707
Maximum	2.123	2.172	2.255	2.356
Summary	Mean of Calculated is 0.010kPa lower than observed pressure.	Mean of Calculated is 0.085kPa higher than observed pressure.	Mean of Calculated is 0.101kPa higher than observed pressure.	Mean of Calculated is the same as observed pressure.

The summary table above gives an indication of how closely the calculated values for MM Barometric Pressure match the observed values during the period 2015. The mean of the differences between observed MM pressure value and the result of each of the four different calculation methods gives an indication of how accurate the calculated value is compared to the observed. As expected, MM Baro from Baro Formula with obs. temp. lapse rate + fixed correction has a mean difference of zero due to the offset applied. The standard deviation figure gives an indication of the spread (random error) of differences, it can be seen that the method using a regression of FB Pressure and GarE stream temperature (Method 1) to calculate MM pressure has a greater spread of errors when compared to 2015 observed data.

4.4.1.1 Final method used to calculate MM Barometric pressure

Of the two methods explored and additional two variations the regression r square values indicate that the method of calculation which produces a result that most closely follows observed data collected throughout 2015 is Method 2a using the Barometric formula to calculate MM pressure from FB pressure and temperature with the standard temperature lapse rate applied. However, the correlation values and r square indicators are also high and very close to each other for the other variations of the Barometric formula method also. Analysis of the differences between observed and calculated values indicate that the method of calculation for MM pressure using the Barometric Formula with observed temperature lapse rate and an offset to remove a fixed bias should give the most accurate output. The Barometric formula is based on a mathematical model of the atmosphere and dry air so might be expected to include a bias or systematic error due to moisture levels and topographical effects on local air pressure.

Formula used to calculate MM pressure from observed FB temperature and pressure:

$$P = (P_b\,(T_b / T_b + 5.633)\ \hat{}\ 4.1364) - 0.101$$

This was written in a suitable format for Excel as follows;

**=(FeshiebridgePressure*(POWER((FeshiebridgeTemp+273.15)/((
FeshiebridgeTemp+273.15+5.632429308)),4.13641122576)))-0.101**

Equation 4-5: Formula used to calculate missing MM pressure data

The interpolation of missing Mòine Mhór barometer data was derived using the equation outlined in Equation 4-5. The stream water level was corrected for atmospheric pressure and a final water level series for the study years, Nov 2013 to Sept 2016, covering 34 months' of fieldwork monitoring was acquired.

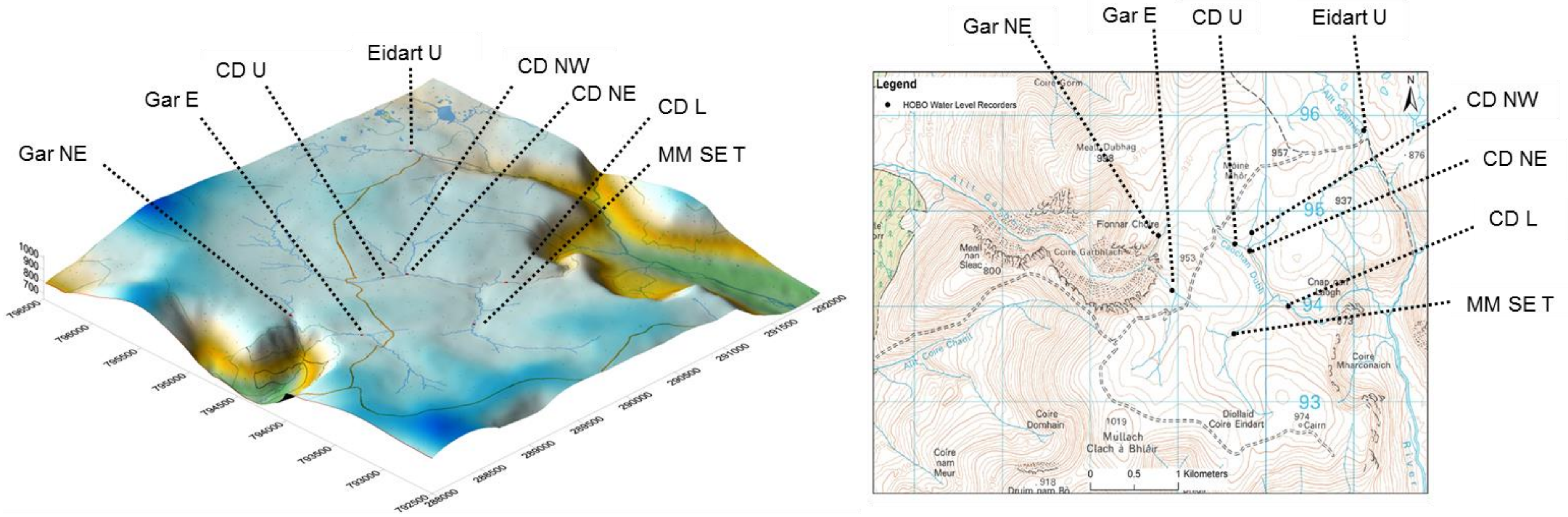


Figure 4-1: Monitored streams on the Mòine Mhór plateau

A 16 km^2 Square *Surfer* plot from *OS DTM* and *Mastermap* data (left) next to an OS map (right). At each location a HOBO data logger was fitted to record stream temperature and pressure. Water samples were also collected at the same location as the fixed water level recorders. The stream names used for each site have been indicated on the map and will be referred to throughout the thesis. *Based upon Ordnance Survey material.*

4.5 Flow gauging

Flow gauging was carried out at the eight monitored streams across the Mòine Mhór to determine stream flow by use of the mid-section method (Figure 4-2). The depth and velocity were measured for a number of verticals along the cross-sectional subsection using the 0.6 depth method. This involves taking a single point mean velocity measurement within each vertical section at 0.6 (60 %) of the water depth (Herschy, 1995; Gravelle, 2015). The two current meters used to determine velocity (Table 4-3) were applicable to the size and flow characteristics of the streams gauged and which meter was taken depended on availability. Table 4-8 outlines the number of times monitored streams were gauged, the typical number of vertical panels for each gauging and mean channel width. The aim was to undertake a number of gaugings on the monitored catchments under a variety of flow conditions.

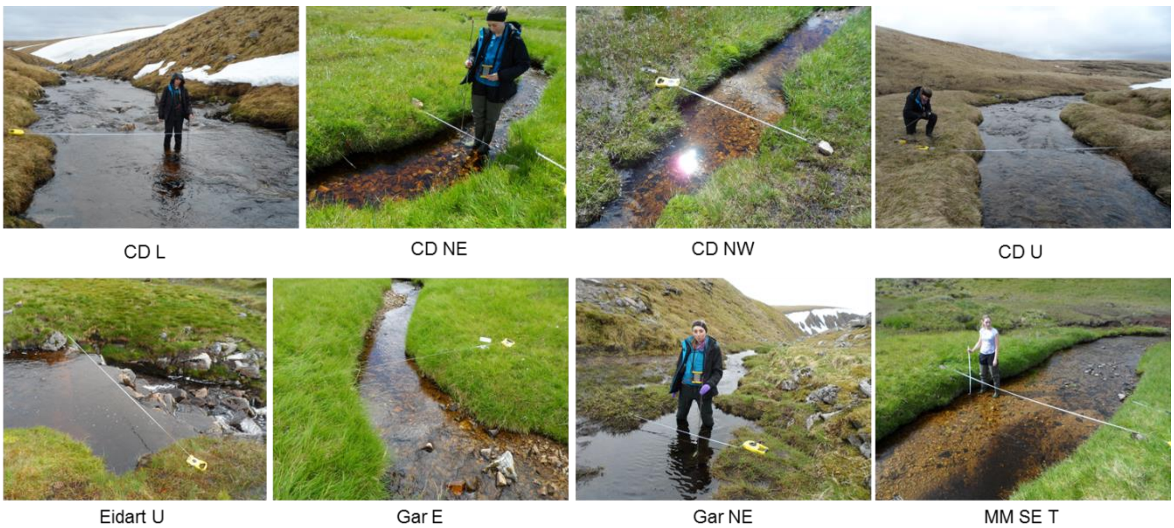


Figure 4-2: The location of flow gauging at monitored streams across the study site

Tape was placed across the width of the channel, the person gauging would do so facing upstream of the flow. The position along the tape, depth and speed would be recorded to derive a value for flow. The same locations were used upon return visits to gauge. These locations were chosen as they contained near uniform flow across the cross section and were seen as representative of the stream.

Table 4-8: Gauging information for each monitored stream across the study site

Number of study visits upon which flow gauging using the 0.6 depth measurement was carried out, the mean number of panels based on individual gaugings and mean channel width based on repeatedly visiting the same section of the stream. The flow gauging period covers from May 2014 to June 2016 and represents a total of 62 gaugings across the Mòine Mhór.

Stream	Number of gaugings	Typical no. of vertical panels for each gauging	Mean gauging channel width (m)
CD L	8	17	4.24
CD NE	7	14	0.93
CD NW	6	10	0.51
CD U	7	12	2.92
Eidart U	9	18	4.46
Gar E	7	12	1.10
Gar NE	7	12	1.01
MM SE T	11	14	2.76

To determine water level and also for QA checks of HOBO data, stage readings were taken manually on study site visits from the vertical piece of angle iron (or horizontal if vertical not suitable/ available at study site) secured into the bank upon which the HOBO logger was attached. The corner piece of the angle iron was used as the reference point (Figure 4-3) and the person taking the reading either measured up or down to the water surface, respectively giving a positive or negative stage reading. A negative reading meant the angle iron was above the water surface and a positive reading meant the angle iron was under the water surface.

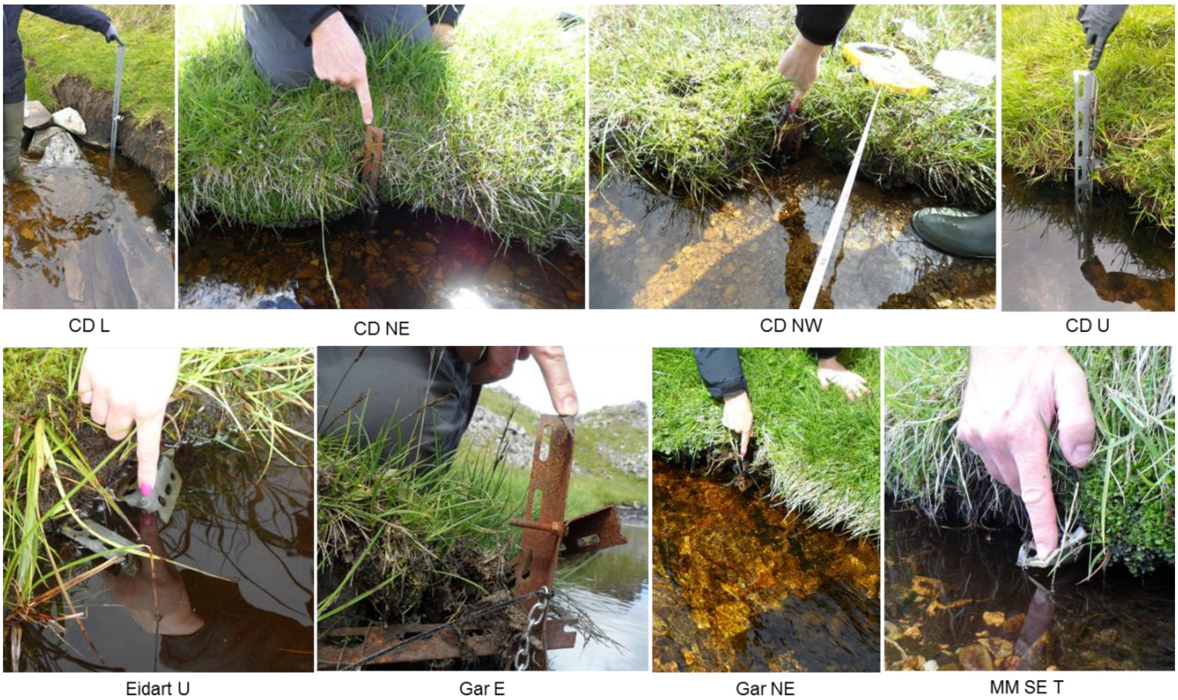


Figure 4-3: Manual stage reference for each of the monitored streams

Stage was recorded from a piece of angle iron secured into the bank upon which the HOBO data logger was secured. Due to the sensitive and exposed nature of this site, this design was implemented to be less visible than the traditional stage boards used for recording stream level.

The results from the OTT C-2 current meter were uploaded to a gauging template spreadsheet. This detailed the distance, calculated width (relating to the position within the channel cross-section in relation to the near and far bank), depth (of water at the pre-determined distance) and rotations (value given per 30 seconds). To develop the cross-sectional area, the depth at each vertical was multiplied by the width, which extends halfway to the preceding and following vertical. Velocities were obtained from Equation 4-6.

$$v = (0.2233\ n) + 0.023 \qquad n < 0.59$$
$$v = (0.2557\ n) + 0.0004 \qquad n >= 0.59$$

Where n = rotations/s and v = velocity in $m^3\ s^{-1}$

Equation 4-6: Velocity measurement calculations using the OTT C-2 current meter

These velocities were multiplied by area in each segment to give flow, such that all segment flow values could be summed to give the flow (in $m^3\ s^{-1}$) on that particular day and at that particular time. The MF-Pro had a digital display screen that carried out the same process automatically; the flow value was calculated automatically by the current meter and was checked before accepting.

Combining the continuous HOBO data with the manual flow measurements to create a rating curve allows the stream flow to be extrapolated for a longer time period.

4.5.1 Creation of flow rating curves

The flow values collected from the gaugings were then used to create the rating curves for each of the monitored streams. A rating curve is the functional relationship between stage and flow. Stage values were taken from the logged level (HOBO logger) and were quality assurance checked against the manual logged level (angle iron secured to bank) to check that there was confidence that when the manual recording of the level was high, the logged level was also high (Appendix C). Where required between downloads, a correction was applied to the logged level taking account of the relationship between the logged and manual levels. If the logger was re-deployed at a slightly different distance from the stream bed, this could be corrected for by either adding or subtracting to the subsequent logged levels to derive a continuous dataset without any step-changes. This was achieved by taking the mean level from the hour prior to removal and adding or subtracting this amount to the next download period. This process was completed between each download period. To account for drift over the dataset, the logged level and manual level were examined in order to derive most appropriate correction to the raw dataset. The logger was repositioned at the same location in relation to the stream bed where possible between data downloads to try to avoid the requirement for corrections.

Flow gaugings that were not deemed representative of the stream flow conditions when comparing the logged and manual levels were excluded in order to derive the most available and accurate rating equation for each of the monitored stream. This helped to maximise the fit of the curve to the selected gaugings in line with professional judgement, site knowledge and hydraulic understanding. However, for comparison, the difference between the rating curves with all gauging and with selected gaugings will be presented in Chapter 5 to present the different iterations explored and provide justification for excluded gaugings.

The accuracy of the gaugings was first checked by looking at the percentage of flow within each panel to check that a representative gauging had been obtained. Next, the relationship between the logged and manual stage in relation to the flow values achieved and notes taken on the day of the gaugings were analysed. A lack of confidence in the relationship between the logged and manual stage, predominately in 2014, resulted in a few gaugings being excluded from the final to obtain a realistic flow data series for the monitored streams assessed by professional judgement. Where multiple gaugings were obtained at the same flows then the most representative gauging was retained. The winter weather conditions resulted in movement of the fixed stage between years making the collection of accurate long-term data series more challenging. The rating curves were created in a hydrological database and analysis software called HYDATA which was used to determine the line of best fit. The rating equations calculated in HYDATA are defined from water level in metres and flow in $m^3 s^{-1}$ and are as follows:

$$Q = a * (h + c)^{b}$$

Where; Q = flow, a and b = rating curve constants, c = zero flow offset and h = stage.

Equation 4-7: Rating curve equation

The equation was then used to derive a continuous dataset for flow which was repeated across the monitored catchments.

4.5.1.1 Annual runoff calculation

The catchment area was calculated using contour data and AutoCAD for each of the monitored streams (Figure 4-4) to allow for the calculation of annual runoff. Displayed in millimetres, annual runoff is a catchment descriptor that quantifies the mean amount of water flowing down a stream per year as a depth of water that is spread across the catchment area.

The National River Flow Archive (NRFA) highlight that an error in the assessment of small catchment areas (< 100 km^2) can substantially affect the runoff value. The values for the Mòine Mhór study streams (0.2 to 4.6 km^2, Figure 4-4) were compared with data available from the wider catchment area (the River Feshie) which has a larger catchment area more suitable for runoff calculations of 231 km^2 and values are presented in Chapter 5.

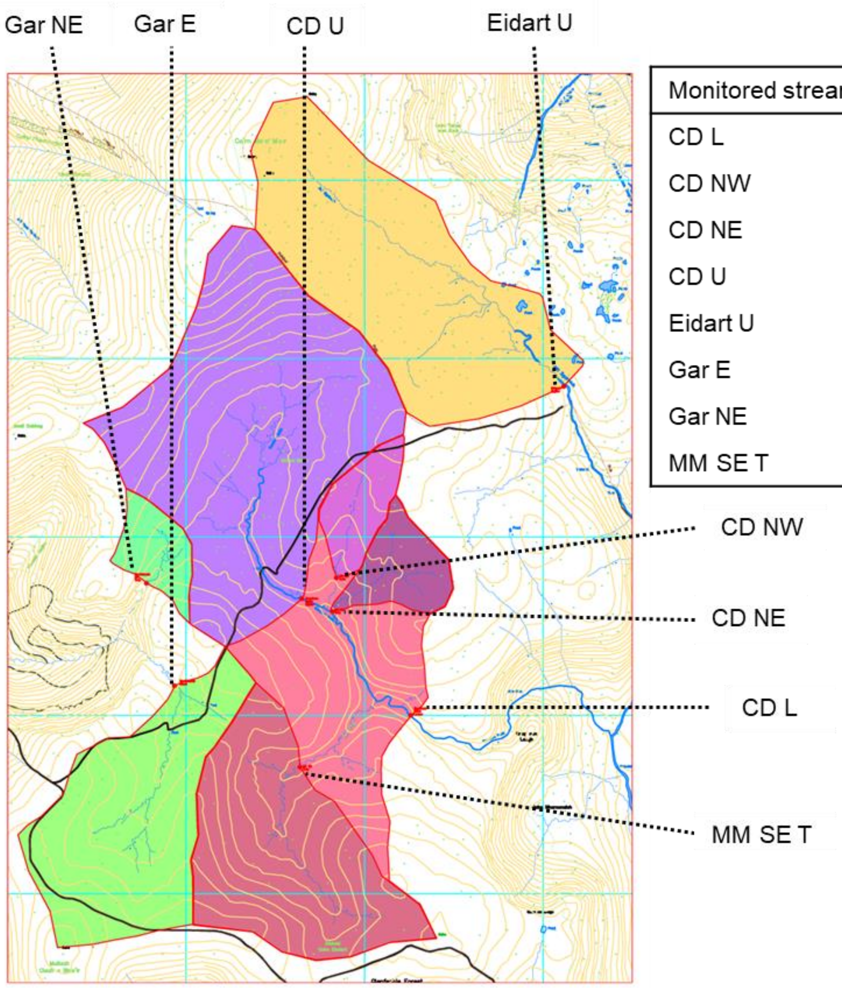
Given the impact of snowpacks in the winter season, runoff was calculated for the summer months for the monitored streams and also compared with complete water years for the study period (2014/15 and 2015/16), however it should be stated that these have been calculated to give an approximate value given the small spatial areas involved.

The Excel equation used to calculate the annual catchment runoff value (in mm) between the years was as follows:

*Annual Runoff Depth = AVERAGE (Flow Start: Flow End) * 60 * 60 * 24 * 365 / (Catchment area * 1000)*

Equation 4-8: Annual catchment runoff calculation

To explain further, flow data was used across the full monitoring period with an average taken. The flow (Q) ($m^3\ s^{-1}$) is required to be converted into volume per year. Multiply the flow ($m^3\ s^{-1}$) by number of seconds in a year (60*60*24*365) to get m^3/year. Then divide by the catchment area (convert area from km^2 to m^2 where 1 km^2 = 1,000,000 m^2). Metres can be converted to millimetres through multiplication to calculate the annual runoff.



Monitored stream	Catchment area (km^2)
CD L	4.61
CD NW	0.21
CD NE	0.24
CD U	2.30
Eidart U	1.61
Gar E	1.10
Gar NE	0.18
MM SE T	1.14

Figure 4-4: Catchment areas of monitored streams on the Mòine Mhór plateau

The delineation of the monitored catchments was carried out using Surfer to create detailed contours from OS DTM data and AutoCAD for plotting catchment boundaries and calculating area. The catchment area represents the area of land where water (surface and ground) collects and drains off into a common outlet such as a river. Surface water comprises rain runoff and snowmelt. CD L is a nested catchment with water draining from MM SE T, CD U, CD NW and CD NE.

4.6 IHACRES rainfall-runoff modelling

Given some of the uncertainties surrounding the level dataset, rating curves and annual runoff values, as highlighted previously (Section 4.3 and Section 4.5), it was decided to utilise another available dataset from a lower site within the Feshie valley to model predicted flows for the study site. The rainfall-runoff modelling method will allow direct comparisons to be made and the outputted datasets and options to be explored further within the results and discussion section.

The IHACRES model requires precipitation data, temperature data and flow data which was uploaded as an hourly time series (15-minute data were unmanageable for the software). The precipitation and temperature data file covered from the 15th of January 2014 to 31st December 2017. The precipitation data was sourced from the Cairngorms AWS and the Eidart TBR (logging since September 2017): the average of both if available, or otherwise one only. The provision of data from CEH for the Cairngorms AWS is gratefully acknowledged.

The flow data was taken from another HOBO water level logger that was deployed at the lower Eidart at NN 91200 88550. The hourly flow file covered from the 11th July 2017 to 4th November 2017. The corresponding barometric logger located at NN 83765 94089 was used to convert the pressure data into a value for water level as outlined in Equation 4-1. The lower Eidart site was located 8.2 km downstream of the Eidart upper site at 550 m AOD. Flows from this site were scaled by ratio of catchment areas for the Mòine Mhór south east tributary site. The data was modelled on the Mòine Mhór south east tributary catchment as this was decided as most representative of the monitored streams on the study site. The Mòine Mhór south east tributary was also more intensively monitored throughout the field work campaign in comparison to the other streams further justifying its choice. The preference is to use the site-specific catchment data when available. However, the modelling approach has also been utilised as a comparison test in order to ascertain confidence in datasets captured.

The general approach to using IHACRES is to find a model which delivers optimum performance as measured numerically while at the same time inspiring confidence qualitatively by visual inspection of simulated hydrographs. The user has freedom to choose between five model structures and is also free to define the calibration period used. Values for six non-linear module parameters can be obtained empirically, by the software iteratively working with all available permutations of the six parameters available (see Figure 4-5), between limits and at increments defined by the user (Croke *et al.*, 2005). To illustrate the process for the Mòine Mhór south east tributary, this proceeds as follows:

- the hourly precipitation, temperature and flow data files were uploaded;
- the FEH flows catchment area of 1.12 km^2 was input;
- the uploaded data was viewed;

- the calibration period was set from 19th Jul – 29th Oct 2017 (low-flow periods near the start and end of the record);
- the cross correlation was run and the IHACRES calculated delay of 2 hours between precipitation falling and stream flow response was set;
- Instrumental Variable checkbox was ticked and then moved onto the Grid Search;
- different iterations of the Pre-Grid Search were run to come up with the best fit to the model;
- the instrumental variable selected was the 'Exponential Store and Instantaneous Store in Parallel (1,1) store configuration with further information in the fitting of models available in the user guide (Croke *et al.*, 2005);
- a selection of the best-performing parameters sets (candidate models) was chosen for further investigation;
- the model selected for simulation had an r^2 of 0.405;
- in the analysis tab, the parameters selected upon accepting the calibration were;

The following non linear module parameters have been set for calibration period 1.

mass balance term (c)	0.371817
drying rate at reference temperature (tw)	0.700000
temperature dependence of drying rate (f)	2.000000
reference temperature (tref)	20.000000
moisture threshold for producing flow (l)	0.000000
power on soil moisture (p)	1.000000

The following linear module parameters have been set for calibration period 1.

Recession rate 1 ($\alpha^{(s)}$)	-0.993		Time constant 1 ($\tau^{(s)}$)	147.977
Peak response 1 ($\beta^{(s)}$)	0.006		Volume proportion 1 ($v^{(s)}$)	0.923
Peak response 2 ($\beta^{(q)}$)	0.077		Volume proportion 2 ($v^{(q)}$)	0.077

Figure 4-5: Parameters and empirically defined values following the IHACRES model fitting exercise

- the simulation of flows displayed the observed streamflow and modelled streamflow in $m^3 s^{-1}$. The modelled stream flow simulated covered from 15th Jan 2014 to 1st Jan 2018; and
- the flows simulated were then used to produce DOC exports from the spectro::lyser as presented in the Chapter 5.

4.7 Water sampling

Grab samples were collected from the monitored streams (Figure 4-6) at approximately fortnightly intervals during the summer and autumnal months (June – November) and, due to snow covered streams, less frequently during the winter and spring months (December – May). Samples were collected using High Density Polyethylene (HDPE) Opaque Plastic 500 ml sampling bottles with caps. These bottles were deemed of suitable size and volume for the chosen analysis. Collected from the University laboratory, clean sample bottles (dishwater rinsed) were taken for each respective sampling visit.

The samples were collected at HOBO locations (Table 4-4). Flow gauging was also carried out at the same time and at repeated locations by the same sampler. Prior to collecting the water sample, the bottle and cap was rinsed out three times in the stream water which the sample was taken within. The sample bottle was carefully positioned to ensure that sediment from the bed was not captured to allow for an accurate sample collection. For scientific rigour, when possible, three samples were collected from each of the monitored streams. Due to availability of bottles or logistics of carrying excessive loads over long distances by foot (particularly in winter when track was blocked to vehicle) there were occasions where only one sample at a location would be taken. The effect of these single samples on the overall data set was minimal due to the number and frequency of samples collected over the study period. Over the duration of the project water samples were collected covering two autumn, two winter, three spring, and three summer seasons (Table 4-9). Collected samples were refrigerated upon return from the fieldwork and were analysed at the earliest convenience thereafter, often within the same week.

Upon post processing it was discovered that some of the dissolved oxygen (DO) concentrations recorded from the DO meter were not physically possible. These data values have been removed as suspect data and have not been analysed further. This appeared to happen on certain dates for unknown reasons. It is possible that the DO meter was not calibrated / functioning properly as accounting for a change in units did not correct the erroneous values. The range of DO meter was from 0-19.99 ppm and 0-100 %. The dates where values were removed include August 2014, September 2014, October 2014, August 2015 and

September 2015 resulting in 21 % of dissolved oxygen values being removed from the overall dataset.

Table 4-9: Number of water sampling occasions in the eight study streams

The water sampling period covers from May 2014 to September 2016 and represents a total of 191 water samples from across the Mòine Mhór. Although not accounted for in this table, note where possible at each location a replicate of three samples were collected.

Stream	Number of individual sampling occasions
CD L	18
CD NE	23
CD NW	20
CD U	25
Eidart U	17
Gar E	25
Gar NE	21
MM SE T	42

4.7.1 Automatic water sampling

An ISCO 6712 portable surface water autosampler was located at the Mòine Mhór south east tributary (Figure 4-6) to try and capture water samples during high flow events. A level switch was used to allow the sampler to be triggered automatically once the level reached the sensor. This meant that the sampler could start collecting samples at a pre-determined interval once the level had raised enough to cover the sensor. The sampler holds 24 bottles and the aim was to try and capture storm samples when high levels of particulate matter are transported down the stream. Logistical constraints meant that access to the study site during these storm events was difficult but some events were captured across the study period, results are presented in Section 5.8. An additional autosampler was placed on the Garbhlach east to allow for comparisons between streams during event samples. However, issues with the sampler incorrectly filling the bottles and intermittently working meant that this location was not as successful.

Figure 4-6: Water sampling fieldwork activities

Collecting grab samples (left) and the autosampler set-up on the Mòine Mhór south east tributary (right). The autosampler is located on the river bank and is secured to the bank with rope tied to the wooden structure. The power requirements of the autosampler were met by the batteries and solar panels located on the stand visible in the background.

4.8 Statistical analysis

Water chemistry data collected was analysed in Excel using the Data Analysis software package. A 1-way analysis of variance (ANOVA) and a Tukey's multiple comparisons test were selected to explore any significant differences between the streams. The significance of the difference was determined by the calculated p value (Table 4-10). The data assumptions of both tests are randomness and independence, normality tested through analysis of histogram plots and homogeneity of variance. If the ANOVA leads to a conclusion that there is evidence that the group means differ, the next step would be to investigate which of the means are different. A Tukey's multiple comparison test is then used to determine which of a group of differ from the rest.

Table 4-10: Statistical scale for the p value significance rating

p value	Wording	Summary
≥0.05	Not significant	ns
<0.05	Significant	*
<0.01	Very significant	**
<0.001	Extremely significant	***

Regression analysis was also carried out to explore the relationship between variables such as for the water chemistry parameters of absorbance and dissolved organic carbon concentration or for the relationship between water temperature and pressure. The outputs are summarised in Table 4-11.

Table 4-11 Regression statistics analysis output

Linear regression analysis also outputs ANOVA values and the linear regression equation y = mx + c, where; y = slope * x + intercept.

Output	Summary	Interpretation
Multiple r	Correlation coefficient	1 = perfect positive relationship, 0 = no relationship
r^2	Coefficient of determination	% of points fall on the regression line / fit the model
Adjusted r^2	adjusts for the number of terms in a model	Use if have more than one x variable
Standard error of the regression	estimate of the standard deviation of the error	the precision that the regression coefficient is measured
Observations	number of observations in the sample	

4.9 Precipitation data

Precipitation data was monitored across the wider Glen Feshie catchment. The monitoring network has been positioned with the aim of capturing a range of altitudes, aspects and geographical variations whilst having regard to practical considerations such as access tracks.

Given the lack of site specific precipitation data, a 5 inch diameter (127 mm) storage gauge was set up on the plateau in autumn 2014 near to the Mòine Mhór south east tributary (Figure 4-7). The gauge rim was sited 30 cm above ground level and comprised of a circular collector and a funnel that channelled the precipitation into a collecting mechanism comprised of a narrow necked plastic bottle placed in a removable can. The storage gauge was emptied on a regular basis during study site visits. The smaller volume size (total of ~ 77 mm rainfall depth equivalent) meant that in relation to the wider monitoring network this gauge filled up rather quickly and would sometimes overflow before being emptied. This makes some of the data unreliable although the gauge does give an indication of the precipitation totals over time on the plateau.

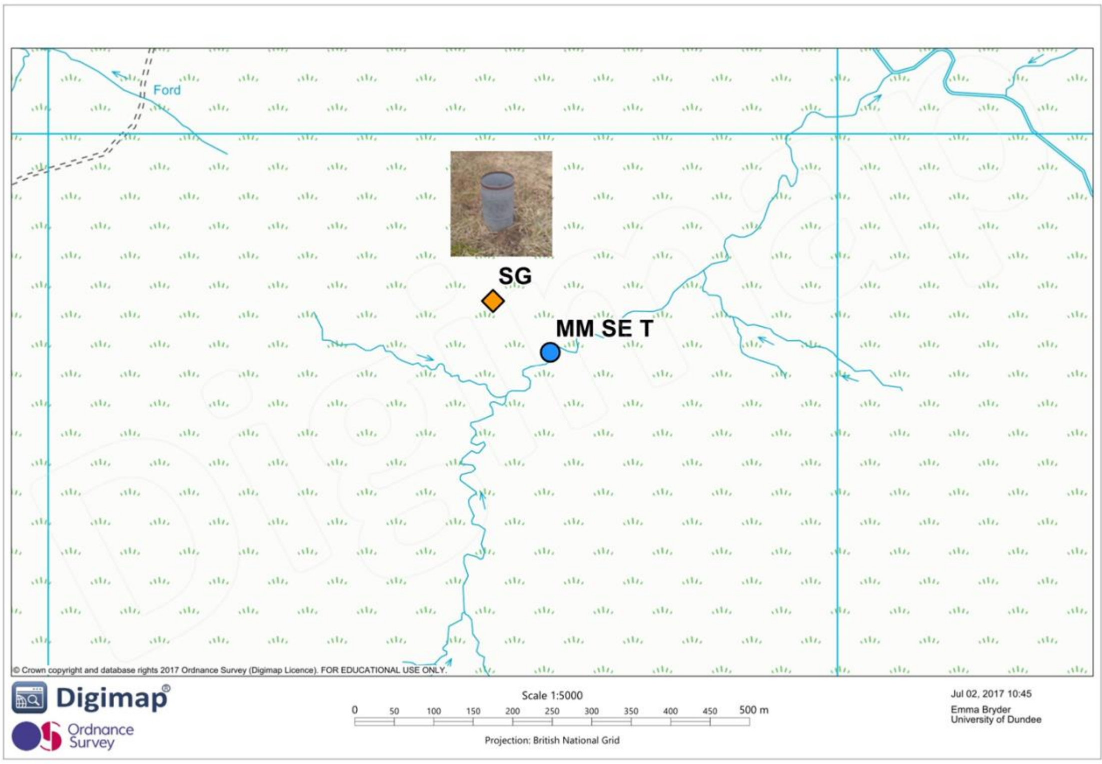


Figure 4-7: Mòine Mhór storage gauge

Inset photograph and map showing the study site specific storage gauge (SG) on the Mòine Mhór in relation to the Mòine Mhór SE tributary (MM SE T). SG positioned at NN 89566 93756 at 907 m AOD. The Mòine Mhór SG was installed in autumn 2014.

In order to gather a more complete picture of the precipitation totals on the study site, the wider network of meteorological equipment in the Glenfeshie area has been drawn upon (Figure 4-8 and Table 4-12). There have been some issues in relation to the network and its reliability but overall there is sufficient data available for the purpose of this study.

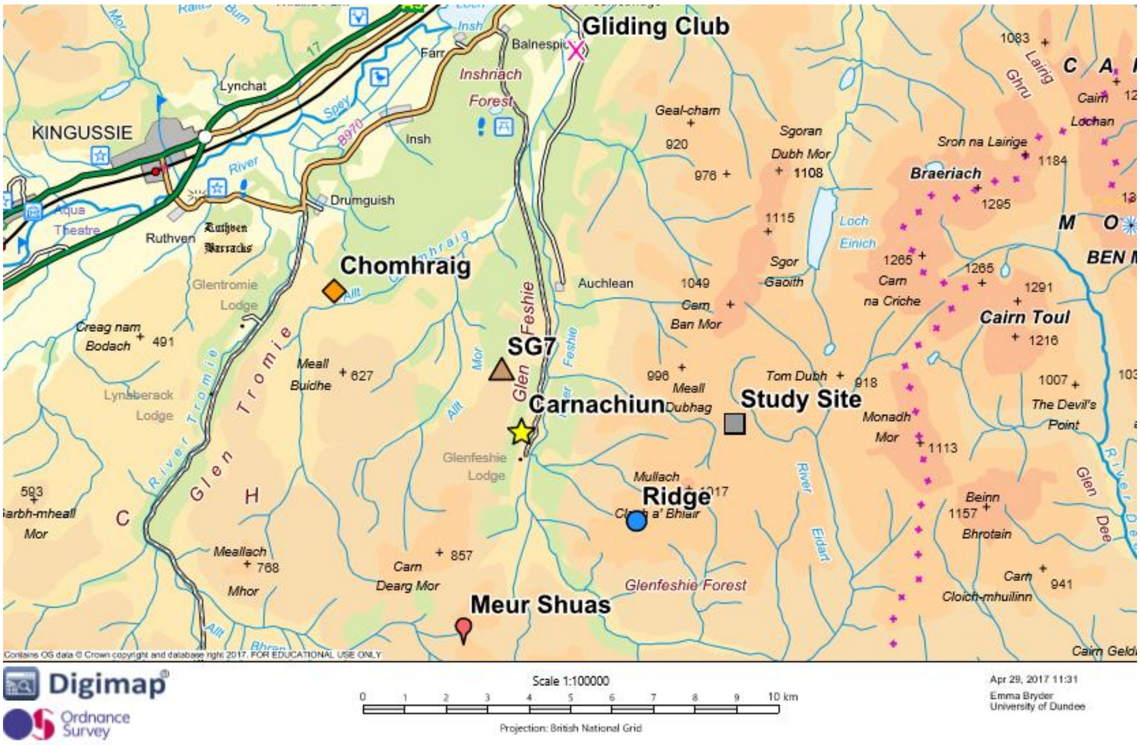


Figure 4-8: Location of meteorological monitoring equipment in Glenfeshie

Precipitation is recorded with tipping bucket rain gauges (TBRs), storage gauges (SGs) and by the use of automatic weather stations (AWSs) which belong to, and are operated by, the University of Dundee in partnership with Wildland Ltd. The grey box highlights the study site with reference to the Ridge AWS (blue circle), Meur Shuas TBR (red droplet), Carnachiun AWS (yellow star), SG7 (brown triangle), Chomhraig TBR (orange diamond) and the Gliding club AWS (pink cross).

Table 4-12: Summary of precipitation data sources

Tipping bucket rain gauge (TBR) and automatic weather station (AWS). In relation to the days of reliable data column, data gaps include issues due to winter weather conditions, blockages and battery problems. Period of interest covers from November 2013 to September 2016.

Equipment type	Site name	Grid reference	Altitude	Distance from Mòine Mhór	Other information	Days of reliable data across study years			
			m AOD	km		2013	2014	2015	2016
Storage gauge	Mòine Mhór plateau	NN 89566 93756	907	0	Capacity of 77 mm. Installed autumn 2014.	N/A	85	266	150
TBR	SG7	NN 83828 95439	489	5.9	Each tip = 0.2 mm	N/A	N/A	N/A	216
TBR	Meur Shuas	NN 83382 89256	692	7.5	Each tip = 0.2 mm	53	245	365	315
TBR	Chomhraig	NN 79800 97400	375	10.4	Each tip = 0.2 mm	60	267	300	365
AWS (TBR)	Ridge	NN 87080 91862	933	3.1	Located at top of Druim nam Bò. Installed 7 August 2015. Campbell CR10X loggers. Each tip = 0.2 mm. Sensors/weather stations supplied by Environmental Measurements Ltd.	N/A	N/A	146	284
AWS (TBR)	Carnachiun	NN 84308 94022	410	5.2	Each tip = 0.2 mm	N/A	N/A	N/A	172
AWS (TBR)	Gliding Club	NH 85613 03214	260	9.7	Each tip = 0.2 mm	N/A	40	153	70

The Ridge automatic weather station (AWS) is closest in terms of altitude and proximity to the study site but this was only installed on the 1st of August 2015. As a result, data from Meur Shuas (tipping bucket rain gauge (TBR)), Carnachiun (AWS), SG7 (temporary TBR), Chomhraig (TBR) and the Gliding Club (AWS) have also been utilised. The AWS and TBR mechanism records an event (tip) each time a rainfall increment of 0.2 mm has been detected allowing the 15-minute rainfall totals (mm) and running accumulations (mm) to be calculated. Across the monitoring network no heating elements were utilised therefore snowfall inputs were only captured at the point at which a melt event happened. As a result data during the winter period is treated with caution. For the storage gauges, the observer emptied the collected rain into a graduated plastic cylinder where readings were taken at approximately monthly intervals. The monitoring equipment available allowed a dataset detailing precipitation totals across the study period to be compiled. The precipitation data gathered has been used in addition to the level, flow and water quality data gathered.

4.10 Cairngorm ECN AWS precipitation data

Across the duration of the study period there were a number of reliability and technical issues experienced with the Glenfeshie network of precipitation data sources (Table 4-12). As a comparison, the dataset has also been downloaded and processed for the Cairngorm automatic weather station (AWS) unheated tipping bucket rain (TBR) gauge (Table 4-13) (Rennie *et al.*, 2017). The Cairngorms AWS (Site code T12) is part of the wider UK Environmental Change Network (ECN) programme which records meteorological data from geographically remote sites, previously discussed in Section 3.5. The rainfall totals were recorded hourly and have been summed to provide daily totals from 00:00 to 23:59 the same day. Again, some data was lost over the winter period due to winter weather however given the extremes of the climate a largely complete dataset was available to be used as a comparative dataset for the purposes of this study.

Table 4-13: Cairngorms TBR data source

In relation to the days of reliable data column, data gaps include issues due to winter weather conditions and blockages. Period of interest covers from November 2013 to September 2016. Supporting documentation downloaded from CEH website provided information on grid reference location (Rennie *et al.,* 2017). Note: data for 2016 has not yet been quality checked by CEH and there may be higher uncertainty in accuracy of this dataset.

Equipment type	Site name	Grid reference	Altitude	Distance from Mòine Mhór	Other information	Days of reliable data across study years			
			m AOD	km		2013	2014	2015	2016
TBR	Cairngorms ECN AWS	NH 89209 04300	698	10.0	Situated in Allt a' Mharcaidh catchment area. New AWS (AWS No 2) installed on 12/09/2007.	51	352	320	260

4.11 Continuous water chemistry monitoring

4.11.1 Spectro::lyser location

A s::can spectro::lyser™ was immersed in a stream draining the Mòine Mhór to provide information on water quality over the duration of the project period (April 2014 – September 2016).

The spectro::lyser was positioned on the Mòine Mhór south east tributary after this location was identified as a suitable location for deployment. This location was chosen due to its positioning away from the footpath, reducing the visual impact on the plateau. The Mòine Mhór south east tributary was also positioned in the centre of the study site and represents the south east sub-catchment of the main stream draining the plateau, the Caochan Dubh.

4.11.2 Spectro::lyser set-up

The instrument records data on total organic carbon (TOC), dissolved organic carbon (DOC), turbidity and colour. The instrument works according to the measuring principles of UV-VIS spectroscopy in the range from 200 to 735 nm (Figure 4-9) and the absorbance is determined every 2.5 nm. Algorithms provided by S::can are used to derive the parameters using a global calibration recommended by the supplier for use at this site. The measurement of DOC concentration is established from over 80 wavelengths, partly to calculate the concentration but mostly to correct for turbidity (Koehler *et al.*, 2009).

The recording interval was set at 15-minutes, which required a visit every 17 days to download and manually clean the instrument. The time interval was programmed to match the 15-minute time stamp of the HOBO water level loggers (Section 4.3.2). When the study site was inaccessible due to snow cover the spectro::lyser was set to record every hour to prevent data loss and conserve battery power.

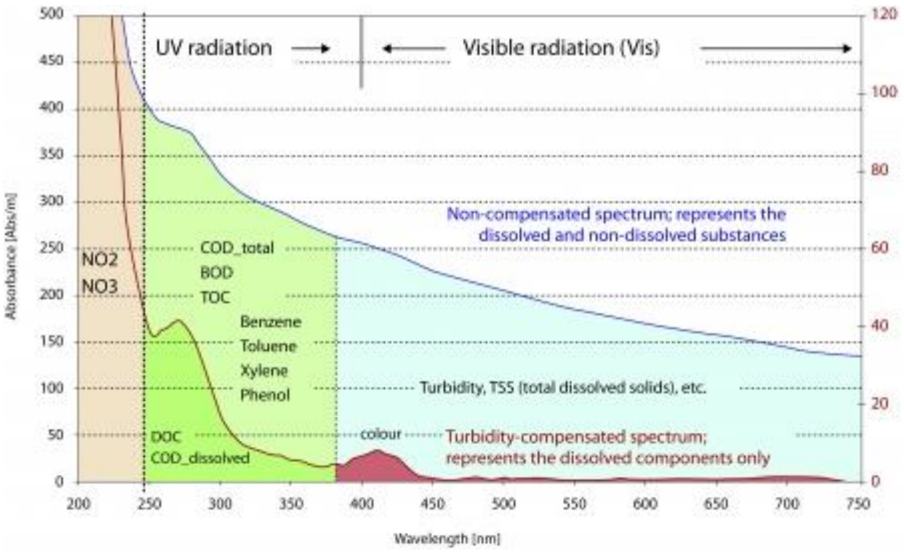


Figure 4-9: Spectro::lyser graph

The spectro::lyser is a spectrometer probe that measures the entire UV and visible absorption spectrum allowing selective and accurate simultaneous measurement of multiple parameters with a single measuring device (S::can, 2016).

4.11.3 Spectro::lyser deployment

There was a general lack of guidance available, historical or otherwise, regarding the installation and mounting of the spectro::lyser, with various methods trialled by others (e.g. suspended from a drain pipe). Therefore some details regarding the mounting and installation of the acquired spectro::lyser have been provided. Two 12 V batteries were wired in parallel and charged by two 43 W solar panels (specifications in Table 4-3). One battery was used to power the spectro::lyser and the other battery was used to power the autosampler and dissolved inorganic carbon (DIC) probe (instrument described below). Generally, this set-up was able to maintain the power demands of all instruments even throughout the harsh winter months. The unit was placed in a horizontal orientation in the stream with the plane face of the measuring path in a near vertical position (as illustrated in Figure 4-10) to minimise blockage of the measuring section by a build-up of particles present in the water.

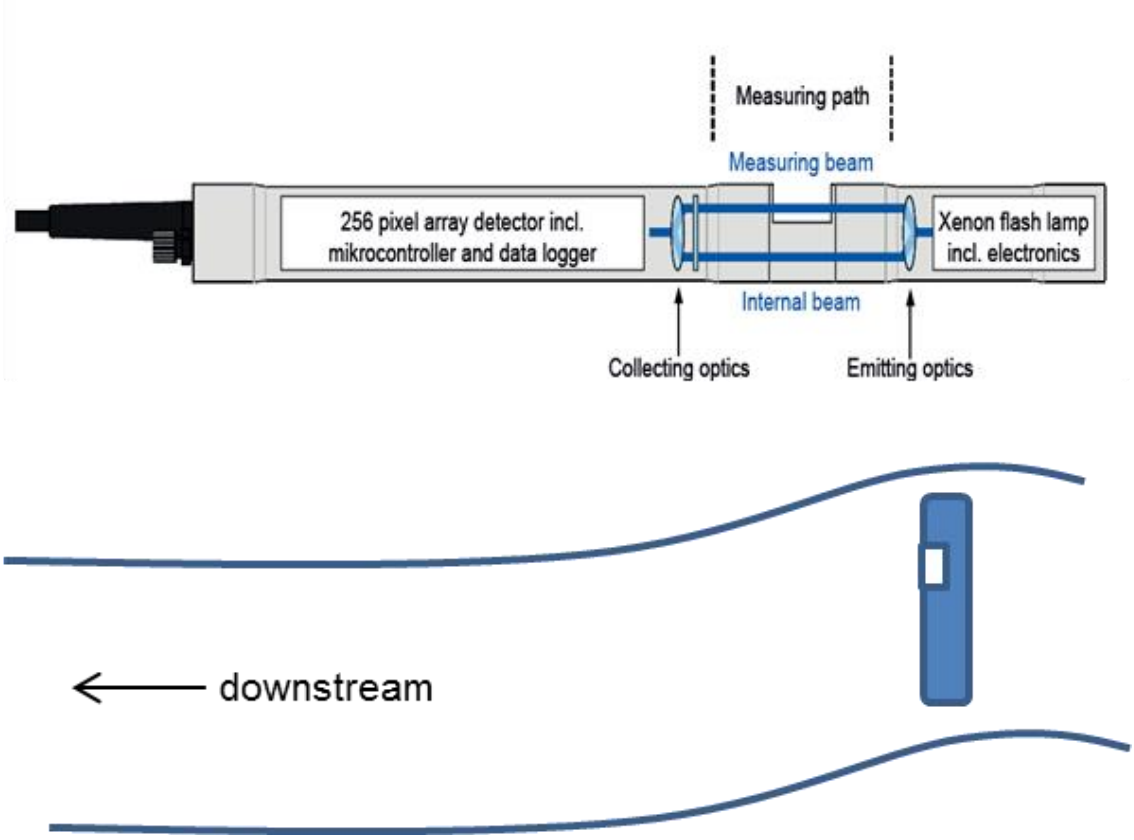


Figure 4-10: Measuring path and orientation of the Spectro::lyser in stream

A schematic representation of the spectro::lyser is shown above and below is the spectro::lyser shown in stream with the white block in the instrument representing the positioning of the measuring window during deployment.

Initially, the spectro::lyser was placed in a custom built cage (Figure 4-11) as it was thought that the cage would provide protection from stream debris that may cause damage to the instrument. However, it was discovered that the cage caused particulate matter to build up, thus making the readings of turbidity artificially high. A new mounting installation was subsequently designed and implemented. This consisted of the suspension of the spectro::lyser from a log that was fixed over the width of the river bank. A bracket was designed, created and subsequently attached to a log. The custom design of the bracket allowed for an upward and downward movement which gave flexibility in positioning the spectro::lyser at various depths within the stream channel (Figure 4-11). Generally, the spectro::lyser was placed one third of the way up from the stream bed. Of note, the instrument suffered no damage as a result of not being protected. The log design generally worked very successfully but the logs did bow and snap under the pressure of the melting snowpack. If this design is to be repeated in a similar arctic-alpine environment this would need to be taken into account. At each measurement the probe detects the absorbance due to the full spectrum of wavelengths being passed through the measured medium. As highlighted in Figure 4-9, the wavelength and absorbance measurements allow for the measurement of multiple parameters such as turbidity, total organic carbon, dissolved organic carbon, colour and nitrate.

Figure 4-11: Mòine Mhór SE tributary field instrumentation for the spectro::lyser

Set-up in summer and winter (a & c) and location within the plateau (b). The cage was first used to deploy the spectro::lyser in June 2014 (e) and subsequently the adjustable bracket was designed and used thereafter (f). The spectro::lyser, autosampler and DIC probe were powered by solar panels and batteries (d & g).

4.11.4 Spectro::lyser operation and maintenance

A software controlled global calibration data file was provided with the probe, consisting of a set of spectral algorithms tailored to suit particular applications and corresponding outputs. The specific global calibration tailored to the river water environment was loaded onto the probe prior to deployment under the supervision of the supplier. The calibrated probe was then deployed into the stream and did not require a subsequent calibration following deployment.

The optical window is where the measurement takes place so it was important that the instrument was cleaned regularly to prevent the built up of particulate matter e.g. sediments and algae. The instrument was cleaned with a cloth and soft brush with particular attention placed on cleaning the optical window and was rinsed with distilled water after cleaning. The housing unit was occasionally cleaned with an ethanol solution to remove stubborn staining applied using a cloth and rinsed with distilled water after cleaning. Two light beams are used by the instrument, one is used as a reference beam and the other passes through the sample. This internal referencing system guarantees the long-term stability of the signal produced, even when the beams are partly affected by surface deposits.

Although the spectro::lyser was primarily designed for *in-situ* operations it was also suited for use as a bench-top instrument. This was achieved in the field by removing the instrument from the stream and fitting an adapter which allowed other stream water samples to be tested from the river bank. Before and after other samples were tested, the instrument was rinsed with distilled water. Each water sample collected was analysed three times in a row and an average taken. Each time the probe was used as a bench-top instrument, the probe was checked in distilled water to ensure that the probe was still reading accurately. After use on the river bank the spectro::lyser was re-deployed in the stream at the same depth and position. Communication with the probe was managed through the Ana::pro software package and a laptop running Windows XP Pro 32 bit.

4.12 Inorganic carbon monitoring

Another instrument was deployed in March 2015 after the success of a small grant application by Dr Tom Ball, which added to the monitoring network on the Mòine Mhór. The DIC probe was adapted for the water environment to try and capture the inorganic carbon budget of the streams draining the Mòine Mhór. The DIC probe took a measurement of dissolved CO_2 and the temperature of gas (°C) every 30 minutes and was provided by the batteries for the other field instrumentation wired in parallel.

The Vaisala Carbocap NDIR sensor is usually used in air. In order to make it suitable for deployment in water it was sealed into a water tight (gas permeable) housing prior to submersion in the Mòine Mhór south east tributary stream. This is a proven modified headspace method and the methodology is described in more detail by Johnson and colleagues (2010). Figure 4-12 illustrates how the sensor was made watertight for the Mòine Mhór south east tributary but remained gas permeable.

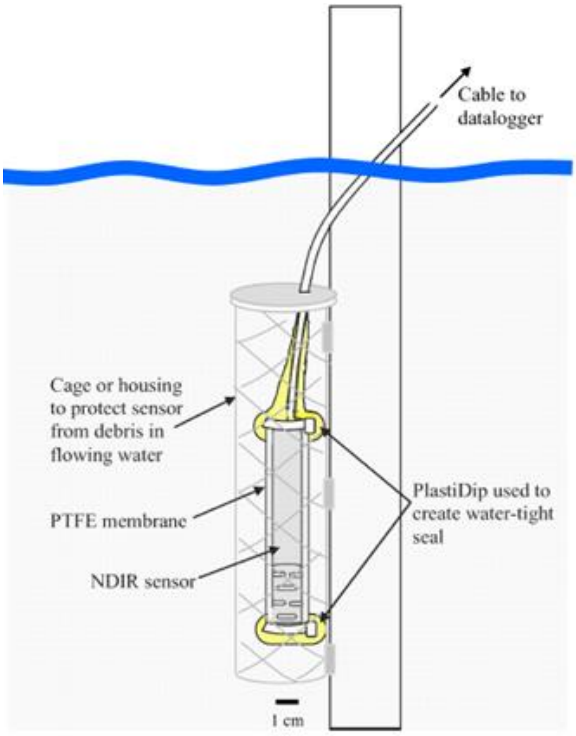


Figure 4-12: Method used to make Vaisala Carbocap sensor watertight

The method illustrated above effectively uses a modified headspace method with dissolved CO_2 present in the stream water equalising with the gas at the sensor through the gas permeable polytetrafluoroethylene (PTFE) membrane. Source: (Johnson *et al.*, 2010).

To supplement the inorganic data collected, gas samples were also taken on a number of occasions at the study site using the headspace sampling technique (Kling *et al.*, 1991). Headspace gas samples were taken on 11/03/15, 20/04/15 and 15/05/15 for analysis by Gas Chromatography (GC) at CEH where concentrations of DIC, CO_2, CH_4 and N_2O were measured. A standard method was used to collect the headspace samples from the stream whereby a 40 ml water sample was taken at the appropriate depth, 20 ml of air headspace was introduced and then the sealed syringe was agitated underwater for 60 seconds to equalise gas content before transferring the headspace sample to a vacuum sealed vial for later analysis. In addition to the gas sample, ambient air samples were also collected by extracting 60 ml of air from the stream bank where the headspace samples were taken from. All samples collected were kept in a dark cool box until analysis. The headspace gas collected was analysed by gas chromatography at CEH, Edinburgh to determine the dissolved gases in the sample. Concentrations were calculated using the principles of Henrys Law and water temperature, atmospheric pressure and elevation.

4.12.1.1 Correction of Vaisala Carbocap sensor readings for pressure

The Vaisala Carbocap NDIR sensor reading is affected by ambient temperature and pressure (units are factory calibrated at 25°C and 1013 hPa (average sea level pressure)). The GMP343 sensor used included a temperature sensor and automatically compensates the output for temperature but the CO_2 value logged also needs correction for the pressure difference from the calibration value due to air pressure on site and hydrostatic pressure from submersion in water. The Manufacturer literature specifies that the output from the probe should be compensated in pressures below 1013 hPa by adding 0.15 % of the reading for every 1 hPa that ambient pressure is below the calibration value (Vaisala, 2019). The Vaisala Carbocap sensor was deployed at the same depth as the Mòine Mhór south east tributary Hobo pressure sensor which meant that each CO_2 reading from the instrument could be compensated for actual pressure at the sensor (combination of atmospheric pressure and hydrostatic from changing water levels) to give a corrected value for CO_2 ppm. Raw CO_2 concentrations (corrected for temperature only) and corrected CO_2 concentrations (corrected for pressure using Mòine Mhór south east tributary Hobo data) are shown in Figure 4-13.

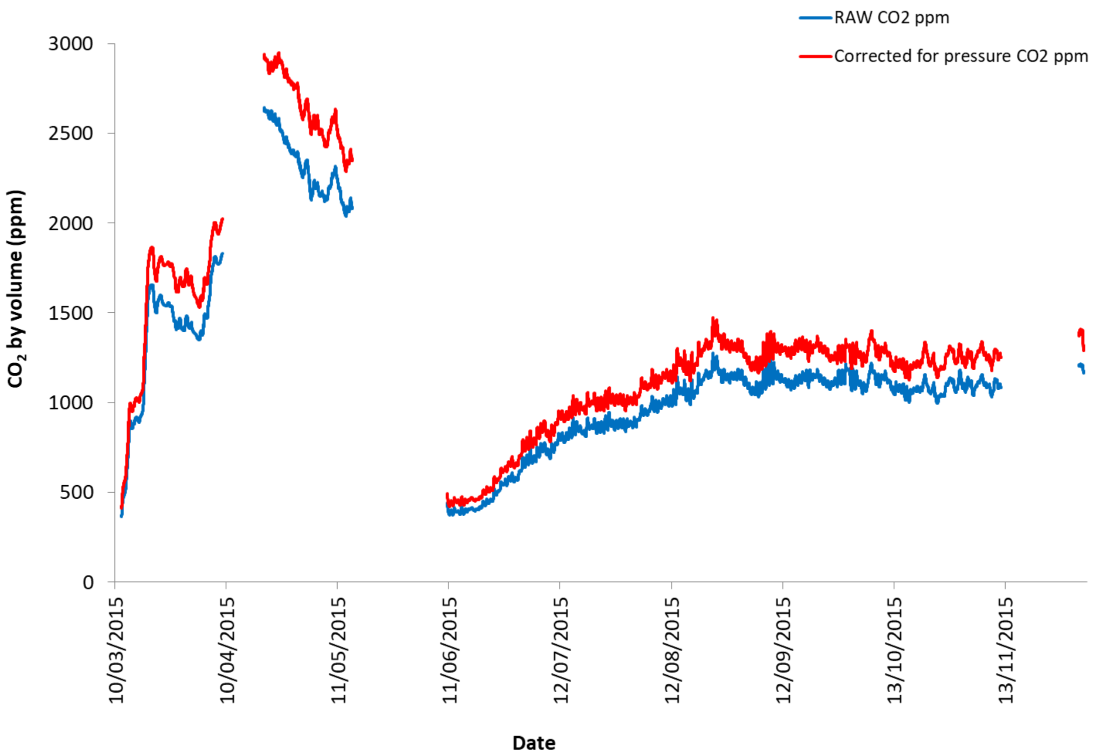


Figure 4-13: Vaisala Carbocap CO_2 readings, raw and corrected for pressure

Dissolved CO_2 ppm readings from the MM SE T throughout data collection period (10/03/15 to 06/12/15) whereby the raw sensor readings are plotted in blue and readings after correction for pressure are shown in red.

The DIC probe took measurements from March 2015 to December 2015 when it was washed downstream and lost due to snowpack/flooding in December 2015 (which corresponded to highest water levels on record since 1992 for the River Feshie).

4.13 Erosion

In addition to the hydrological monitoring, localised surveys were carried out in order to try and build up a greater understanding of erosion at the study site. These related to observing processes of peat movement. A peat block survey was carried out on monitored streams draining the Mòine Mhór. This was carried out by walking along the near and far bank side of the stream (varying in length from 50 m to 250 m dependant on the stream and accessibility). The width of land surveyed was 5 m out from the stream bank, this represented how much was visible to the eye when one surveyor would walk down and then back up the length of the surveyed area whilst being able to observe the ground thoroughly. The same surveyed sections were undertaken on 30 September 2015 and then repeated on 30 September 2016 to see if there had been any changes. Any block of peat that was sitting loose on the surface and was within the designated survey zone was included. The position was recorded with a GPS and the length, width and depth was recorded. These measurements allowed a volume of loose peat in m^3 for each of the monitored streams to be calculated. This small study was carried out to try and capture how much peat is contained in loose blocks that could have the potential to be transported into the stream channel and thus contribute to the organic carbon budget of the study site. GPS tagged photographs and field observation were also utilised to gain a greater understanding of the processes of erosion currently ongoing at the study site.

A design idea was implemented to try to capture and quantify how much peat was moving due to wind and rain erosion. Astro turf mats (0.5 x 0.5 m) were secured to the ground with tent pegs and placed at five locations across the study site. In addition to this, three buckets (30 litre volume) with the bottom cut out and replaced with a fine mesh secured to the end (to trap the organic matter) were also placed at the same locations as the mats. It was hoped that these two methods would trap peat deposits from wind-blown erosion on the plateau or in some deployment locations possibly capture overbank sediment during high flow events.

Details of the location and set up of the mats and buckets are provided in Table 4-14 and Figure 4-14. The aspect has been noted as it was considered that this would have an influence on the transportation of sediment into the bucket which has one opening whereas the mats are exposed to the elements at all sides.

Table 4-14: Location and position of astro turf mats and buckets

	Grid Reference	Description	Aspect
Astro turf	NN 91041 95813	Eidart upper	-
	NN 89878 94505	Caochan Dubh	-
	NN 90240 94020	Caochan Dubh lower	-
	NN 88931 94170	Garbhlach east	-
	NN 89587 93701	MM SE T	-
Bucket	NN 91046 95812	Eidart upper	S
	NN 90254 93390	Caochan Dubh	W
	NN 89589 93650	MM SE T	NE

Figure 4-14: Picture of astro turf and buckets in position

The amount of material trapped in the mats and buckets was recorded by photographs and by noting any observations in a notebook. It was hoped that the amount of organic and inorganic material in the samples would be determined in the laboratory using the loss on ignition method. However, not enough material was captured to carry this out.

4.14 Laboratory work

Upon return from fieldwork, water samples were refrigerated in the laboratory (at 4 °C) until analysed, typically within seven days. A brief description relating to each of the parameters (pH, conductivity and DO) is outlined below to allow for an understanding as to what the probe measures and the methods to do so.

The bottom 4 cm of the pH meter electrode was placed in the pre-shaken sample and gently swirled a few times before allowing the reading to stabilise over the course of a few minutes (Hanna Instruments, 1999). A measurement of the amount of hydrogen ions (H-) in the water sample is expressed as a value for pH on the meter on the LCD screen. Calibration was done using buffers of known pH levels by setting the pH meter to those levels (pH 7 and 10).

Electrical conductivity is a measure of the total concentrations of ions dissolved in the water and is a determination of the water ability to pass an electrical current. The conductivity probe was placed in the water sample making sure that the air-release holes were completely submerged (Hanna Instruments, 1996). The probe was tapped and stirred a few times in order to release any trapped air bubbles before recording the conductivity reading in micro Siemens per centimetre (μS/cm) (Hanna Instruments, 1996). Distilled water passes an electrical current poorly whereas water that contains ions such as sodium, chloride, calcium and magnesium are more capable of passing an electrical current. The aquatic organisms differ in their tolerances for conductivity and salinity which is calculated from the measure of electrical current through the water. A 84 μS/cm conductivity standard solution was used to determine the meter's accuracy with adjustments applied to meet the provided standard value.

A measurement of the amount of gaseous oxygen dissolved in the water sample determines the DO levels essential for aquatic organisms. The tip of the DO probe was continually swirled around the water sample to minimise air bubbles on the surface and a few minutes were waited to allow for the probe and sample to equilibrate in temperature (Hanna Instruments, 1995). The DO meter has a membrane to cover the sensor allowing entering oxygen to stay separated. The sensor is polarographic which involves chemical concentration analysis based on voltage. A voltage is activated across the sensor, a current of oxygen that passes through the membrane is created giving a DO concentration which is displayed on the LCD screen in hundredths of parts per million (ppm=mg/L) (Hanna Instruments, 1995). Calibration is carried out in zero oxygen solution or in 100 % saturated air.

Each probe was rinsed with distilled water between measurements. On all instruments, the regular calibration process was carried out in order to increase accuracy, a procedure carried out by Craig Phillips, laboratory technician at the University of Dundee. After measurement of pH, conductivity and DO, the water was then filtered to remove the suspended material.

Whatman microfiber filter papers (diameter 47 mm, pore size 0.7 micron) were wetted with distilled water and then placed in the oven at 200 °C until dry. The filter papers were then weighed to determine their dry weight. The water samples were measured for total volume and filtered through the pre-washed and dried filter papers and vacuum pump to remove the sediment from the sample. The filtered papers were then placed in the oven at 200 °C to dry for 30 minutes and finally re-weighed to determine the difference and this gave a value for suspended sediment. One filter paper was generally used per water samples collected but if there was a high amount of suspended sediment in the water two filter papers were used.

The filtered water sample was then analysed for absorbance on the spectrophotometer at wavelength 254 nm and 400 nm. The spectrophotometer was calibrated with blank deionised water cuvette samples after every six readings. The wavelength 400 nm is commonly used by UK water companies as they must comply with the European Commission maximum colour standard for treated water which is determined at 20 Hazen, equivalent to 400 nm (Watts *et al.*, 2001). Wavelength 254 nm was chosen as it allows DOC to be estimated from the amount of light absorbed (Grieve and Gilvear, 2008). Aromatic humic substances are the dominant component of DOC which absorbs light in the UV allowing the water companies to often use absorbance at 254 nm as a cheaper surrogate measurement (Edzwald *et al.*, 1985). Grab sample bottles were cleaned in the dishwasher before being re-used.

Access to the gas chromatography (GC) and the LabTOC machine at Centre for Ecology and Hydrology (CEH), Bush Estate was set up through collaboration with Dr Tom Ball. The gas samples were analysed on the GC at CEH for dissolved carbon dioxide, methane and nitrous oxide. The technique of GC involves the separation of chemical substances which in this case was carbon dioxide, methane and nitrous oxide, a summary of how it is able to do so is depicted in Figure 4-15.

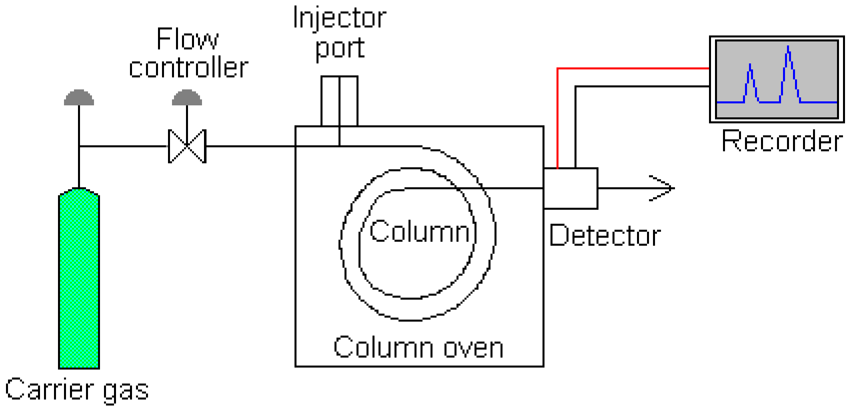


Figure 4-15: Schematic diagram of a gas chromatograph

The carrier gas is an inert gas (e.g. helium or argon); the test sample is injected into this carrier gas via the injector point. The gas passes along the column at different speeds resulting in them dividing up into different substances. The detector allows for the quantification of these substances and the information gathered is output onto the computer which provides a record of the results. The lines on the output indicate the number of compounds present which is inferred from by the number of peaks on the graph. A quantification of how much is present and the length of time it has been retained can also be gathered by looking at the height and width of the peak. Source: (Sheffield Hallam University).

The filtered water samples were analysed in the LabTOC and gave values for dissolved organic carbon (DOC), total carbon (TC) and dissolved inorganic carbon (DIC) (all measured in mg l^{-1}). Total organic carbon contains dissolved and particulate organic carbon and is defined as a measurement of the amount of organic molecules within the filtered water. Sub-samples were loaded into the LabTOC analyser and once set-up, these were left running to analyse for DOC, TC and DIC (Figure 4-16). Standards ranging in concentrations from blanks, 16.67 mg/L, 33.33 mg/L and 50 mg/L were placed in amongst the samples to allow stability to be monitored. Non-purgeable organic carbon (NPOC) measurement is used for TOC quantification in water samples due to the large inorganic carbon component of total carbon (Shimadzu Corportation, 2017). To simplify, the method of analysis for TOC involves automatic sampling, oxidation and detection (Seibel, 2014). Sampling includes the injection of the sample into the sample port, the sample is oxidised to determine levels of TOC and the output signal detection is proportional to the concentration of CO_2 produced as a result this reaction.

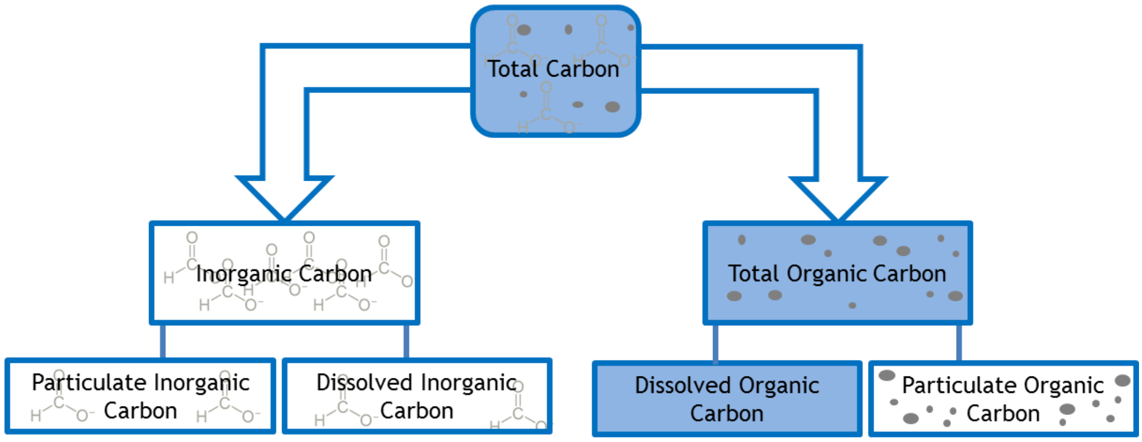


Figure 4-16: Relationship between fluvial carbon compounds

Total carbon measures both the inorganic and organic carbon and can be used as an indicator of water quality. Particulate inorganic carbon includes calcium carbonate ($CaCO_3$) and carbonates of magnesium (Mg), potassium (K), sodium (Na) along with other minerals. Dissolved inorganic carbon includes dissolved carbon dioxide (CO_2), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). Organic carbon serves as a primary food source for aquatic organisms. Dissolved organic carbon is the organic matter that is passed through a filter whereas particulate organic carbon is the larger material that is captured by a filter. Most of the carbon is in the form of dissolved inorganic carbon, a smaller amount is found in the organic form (organic matter and living organisms).

The output of results allowed for a cross calibration of the spectro::lyser outputs with the grab samples analysed in the LabTOC machine. Access to these facilities proved valuable in furthering understanding and providing data relating to the quantification of the aquatic carbon budget of the Mòine Mhór.

4.15 Health and safety

Health and safety was constantly considered during the fieldwork campaign so some lessons learned and guidelines followed have been detailed here. The same study site was visited throughout the duration of the study but an OS map, compass and GPS (with spare batteries) were always carried. The study site was easy enough to navigate on the tracks but if the conditions were poor and visibility was down due to the mist or indeed, as it was much of the time, the study site was snow covered and the track was not visible then these navigation devices were essential as it was quickly realised how easy it is to become disorientated in a featureless landscape. There were issues with the electronic devices due to the cold temperatures (phone not recognising thumb prints, laptop shutting down due to low temperature on occasion). It was found if the GPS was kept close to the chest underneath the layers then this gave it the best chance of it working. Lithium or nickel-zinc rechargeable batteries proved far better than alkaline or NiCad. Dressing appropriately for a day in the hills was essential which required walking boots, base layers, gloves, scarf, hat, fleeces, trousers, waterproof jacket, waterproof over trousers and spares in case the wind chill and rain meant that extra layers were required or dry gloves etc. to change into.

An off-road all-terrain vehicle (ATV) buggy was provided by the estate as transport, which was always kept to the path to minimise impact on the fragile and delicate landscape. The buggy was not used frequently during the winter months when the track was snow covered or when the river level was too high to safely cross. The Carnachuin Bridge that crossed the River Feshie was swept away on 3 September 2009 by a large flood and has not since been replaced. This means that to get access to the Mòine Mhór, the River Feshie must be forded where the bridge was once located. To check if the river level was safe for crossing, the SEPA water level data for their Feshiebridge gauging station was regularly checked (Scottish Environment Protection Agency, 2016). This was used a reference of whether to expect high, medium or low river levels. Generally, below 0.75 m was considered safe to cross in the buggy. On each study site visit someone would be alerted to my plans, the car was parked at the estate, and a radio was taken in case anything was to go wrong. Where possible, someone would accompany me for safety reasons particularly during the winter months due to the harsh conditions and remoteness of the study site. During the summer months, an undergraduate dissertation student would accompany me, Michael Delpippo (summer 2014) and Fiona Scott (summer 2015). These students were looking at flora abundance, diversity and red deer density on the Mòine Mhór. For further details refer to study site specific risk assessment in Appendix D.

5. Results

5.1 Introduction

Water is required for all life on earth, covering 70 % of the earth's surface, however only 3 % is freshwater (El-Bahi and Inan, 1999). The freshwater resource provides important environmental, social and economic benefits to society. The average person in the UK uses 150 litres per person per day, globally a colossal 10 billion tons of freshwater is used daily (Allan, 2010; Consumer Council for Water, 2018; Larsen *et al.*, 2018). Therefore, water quality is important for many aspects of life including the ecosystem habitat, human health, recreation and tourism. Factors affecting the quality of the water can be determined for its purity by colour, smell and taste. However, clear water may still contain impurities that cannot be detected by the human senses alone. To detect such impurities, measurements of the biological, physical, chemical or aesthetic properties of the water can be tested.

The distribution and movement of water is essential for survival (UK Marine SACs Project, 2001; Martino, 2003). Where water is present, the hydrological pathways by which it can move through the environment include surface runoff, throughflow, groundwater flow and percolation. These pathways control the dominant amount of carbon entering the stream (Dawson *et al.*, 2001) (Section 2.6.6). The movement of carbon within the water environment is topically relevant with regards to capturing carbon emissions to mitigate against recent anthropogenic climate change (Section 2.6.3). However, questions still remain regarding how much carbon is lost through the streams.

For the purposes of this project, the data presented provides insight into the extent and condition of the Glenfeshie Mòine Mhór with reference to the water draining from the plateau. A hydrological comparison of the catchments is presented followed by water chemistry data. The variations between catchments are explored and the collected precipitation data is incorporated with reference to high flow events. Actively eroding peatlands contribute to the aquatic carbon budget and a study of loose peat sitting on the monitored catchment river-banks aims to quantify this aspect of the carbon budget. A summary of the aquatic carbon budget based upon data collected for the Mòine Mhór is then outlined.

5.2 River Feshie level and flow rates

5.2.1 Location to study site

An important site for the study of fluvial geomorphology and one of the best examples of a braided river in Britain is the River Feshie with its steep glen, recurrent flash floods and the active undercutting of slope and terrace deposits by the river (Gordon *et al.*, 2006). The River Feshie is located at the foot of the Cairngorms and represents an important site for Scotland's geology as it allows for the study of active and channel landform change in the present and past (Gordon *et al.*, 2006). The catchment area draining to this gauging station is 231 km^2 inclusive of the Mòine Mhór plateau, hence its relevance to the study (Figure 5-1). The Scottish Environment Protection Agency (SEPA) continuously record the water level data of the River Feshie at their Feshie Bridge Station (232 m AOD) (Figure 5-2).

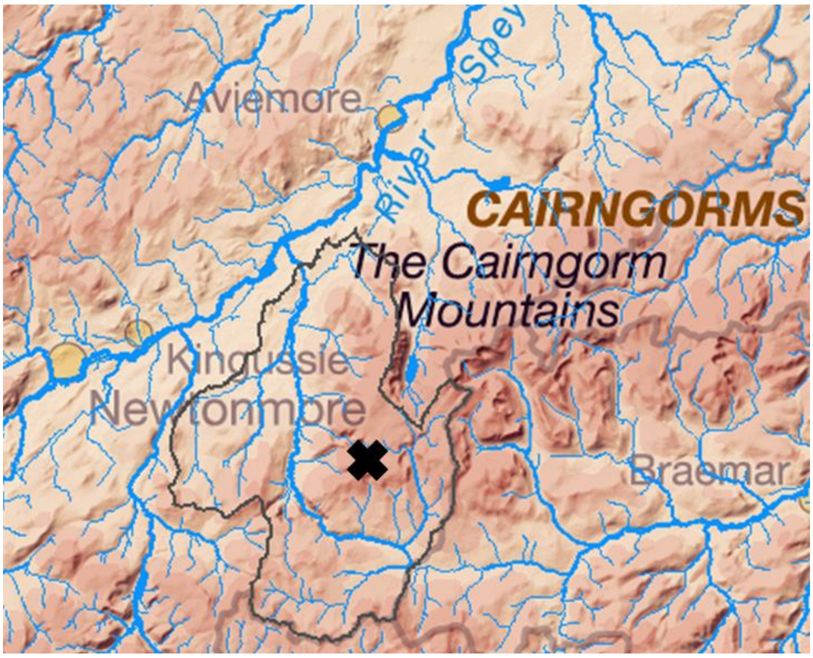


Figure 5-1: Catchment boundary for the Feshie at Feshie Bridge

The Feshie Bridge Station operated by SEPA is part of the Spey hydrometric network. The above image shows the catchment area for the River Feshie (black outline) and the location of the study site within the boundary (black cross). *© NERC (CEH) 2012. For Great Britain: Contains Ordnance Survey data © Crown copyright and database right 2012.*

5.2.2 River level

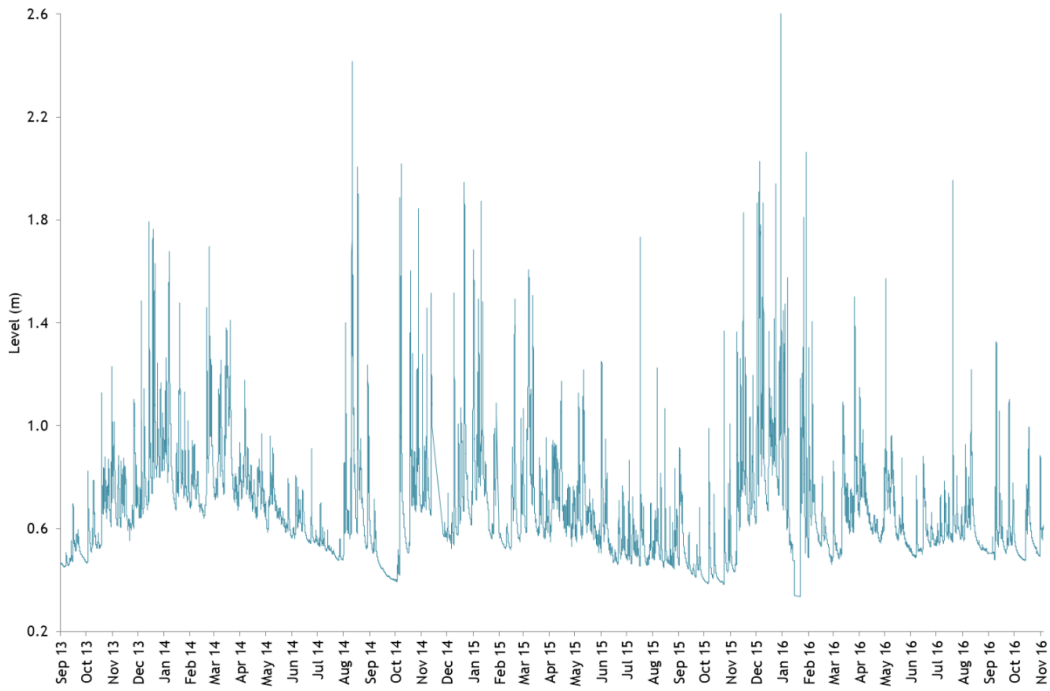


Figure 5-2: Feshie river level from 1st September 2013 to 4th November 2016

Data collected from SEPA Feshie Bridge Gauging Station (Grid Reference NH 84986 04711). The river level was monitored by use of a data logger/ electronic sensor and allows for the calculation of flow. The level was recorded every 15-minutes. The highest river levels of greater than 2 m were recorded on 11th & 17th August 2014, 8th October 2014, 5th & 30th December 2015 and 29th January 2016. Snowmelt and rainfall primarily drive these peaks in levels. The lowest river levels of less than 0.4 m were recorded on 30th September 2014, 1st to 3rd October 2014, 1st to 6th and 18th to 24th October 2015 and 15th to 22nd January 2016.

Long term recording of level data can be used to calculate flows in the river and is beneficial in relation to water abstractions, river engineering, flood forecasting and climate change modelling. The highest level on record, since December 1992, of 2.72 m was recorded on 30/12/2015 at 12:15 GMT. The largest event recorded on 30th December 2015 took place over 35 hours with the peak level of 2.72 m recorded 12 hours after the start of the event. The arithmetic mean level from the record start date of 1992 is 0.77 m whereas the arithmetic mean level for the data graphed in Figure 5-2 is 0.67 m. The arithmetic mean is susceptible to the influence of outliers or skewed values in river level therefore the lower median value of 0.62 m would be considered more representative of the baseflow value of the River Feshie. The lowest level across the study period of 0.34 m was recorded in the period from 15/01/2016 14:00 GMT through to 22/01/2016 06:45 GMT attributable to freezing temperatures where the water was locked up in snow packs within the upper catchment area (Figure 5-3).

Figure 5-3: A snow covered upper Feshie catchment area reflective of winter conditions

Photograph taken from the study site on 6th January 2016, with the Coire Garbhlach to the east and the observer looking north west.

5.2.3 Event hydrographs

The Feshie Bridge gauging station is described as an upland catchment with a natural flow regime where gaugings take place on a reasonably stable control that is liable to considerable movement in extreme spates (National River Flow Archive, 2017). At most sites, flow is assessed by measuring the water level and converting it to flow using a rating curve. At Feshie Bridge, a cableway extends from the hut across the river channel which allows a travelling block and trapeze to be winched across for velocity measurements in order to construct a rating curve.

The steep relief of the mountainous catchment means that water can quite quickly reach the river in response to a rainfall event and results in a steep rising limb on the hydrograph. The size and shape of the catchment also impacts on the response of the river to precipitation events, for example, forestry of the lower reaches of the River Feshie helps to intercept the rainfall. To highlight the differences in response to individual event characteristics with reference to the shape, maximum peak reached and time, six hydrographs for the River Feshie have been displayed in Figure 5-4. The hydrographs displayed highlight the variety of peak flow captured (50 to 120 $m^3 s^{-1}$) across the complete record period (1992 – 2016) and the response times of the River Feshie to the events vary from four to twelve days. Where available, photographs from study site visits from 2014 to 2016 have been displayed in Figure 5-5 to highlight the volume of water transported and the conditions experienced in the days surrounding the selected peak events.

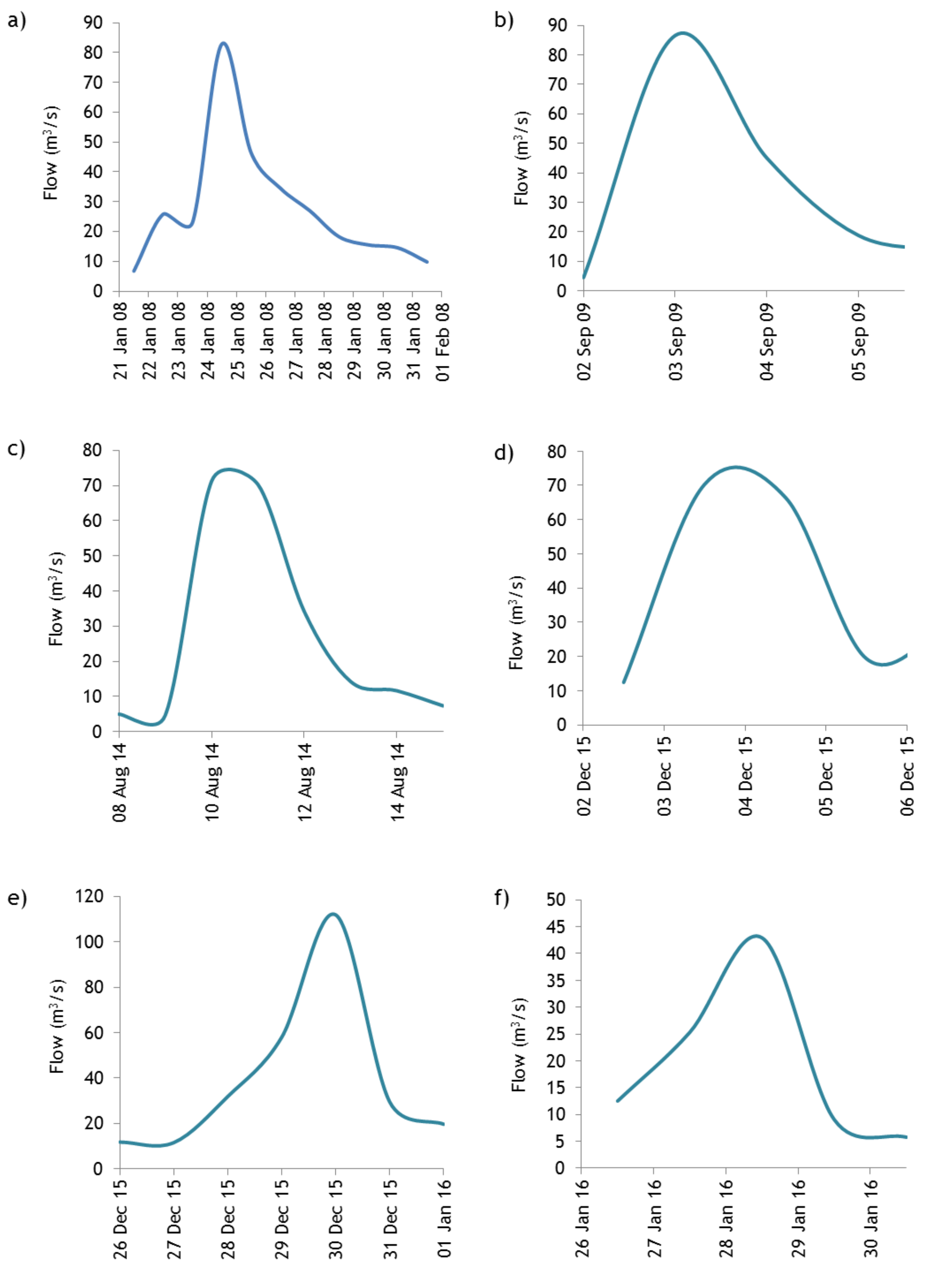


Figure 5-4: Mean daily stream flow hydrographs for the River Feshie

The hydrographs (a-f) display river level peaks of > 2 m during an event. The flow of water during this period is also correspondingly high as seen by the upper limits of the scale in the y axis displayed in $m^3 s^{-1}$. The above graphs illustrate the difference in shape of the event hydrographs from the River Feshie. The response time shown in the x axis captures the rising limb, mean daily peak flow and the receding limb of the event. The x axis range covers a period of 4 days (b) to 12 days (a). *Flow data for the Feshie Bridge Gauging Station downloaded from the NRFA.*

Figure 5-5: Photographs of the wider Feshie catchment during river level peaks

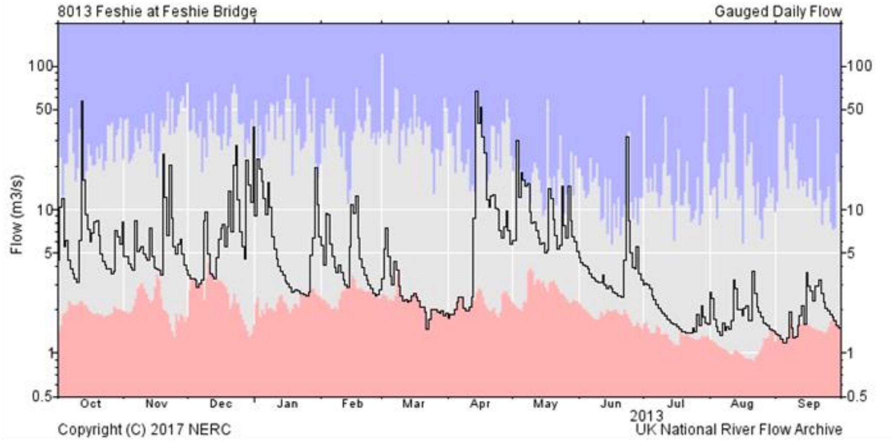
The dates of the photographs shown correspond with the hydrographs peaks in Figure 5-4 to display the wider catchment conditions during and surrounding these events. View of the River Feshie from the ford at Glenfeshie estate (a) and the Auchlean footbridge (b) at 0800 LT on 12th August 2014. On 24th December 2015 at 1000 LT, the River Feshie and the gauging station (c) already elevated prior to the maximum peak on 29th December 2015. A tributary of the Caochan Dubh on the 3rd December 2015 shows a period of snow melt in the upper Feshie catchment (d). No study site visits were undertaken during the event of interest in January 2016 (Figure 5-4 (f)) however, the snow covered upper Feshie catchment can be seen in (e) as lasting into the end of March 2016.

5.2.4 Mean daily flow

The mean daily flows for the Feshie Bridge Gauging Station in water years that cover the duration of the project from 2012 to 2016 are shown in Figure 5-6. The mean flows for water years 2012/13, 2013/14, 2014/15 and 2015/16 were

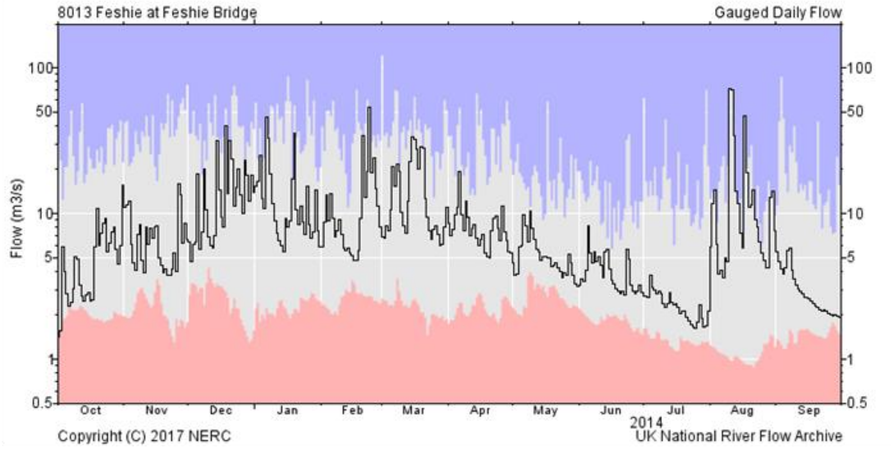
5.87, 8.62, 9.58 and 9.29 $m^3 s^{-1}$ respectively. A trend of increasing mean flow patterns can be noted for every year of this study. A key factor affecting the seasonal flow pattern is the melting of snowpacks and the amount of snow cover in the catchment in the corresponding years. During autumn it would be expected that precipitation would lead to an increase in flow which was observed in 2013/14 after a particularly dry summer season. There was no obvious change in seasonal pattern for flow in 2014/15 where it remained moderately high all year round, supported by the highest mean flow value of 9.58 $m^3 s^{-1}$ indicating a wet year. In autumn of 2012/13 low flows were recorded in comparison to the rest of the year; this water year had the lowest mean flow of 5.87 $m^3 s^{-1}$ with a noticeable drier August in comparison to other years (Met Office, 2017a). Although events can be drawn out and trends discussed, overall, as expected, there was variability between the years and between the seasons in terms of gauged daily flow data for Feshie Bridge, Cairngorms.

a)



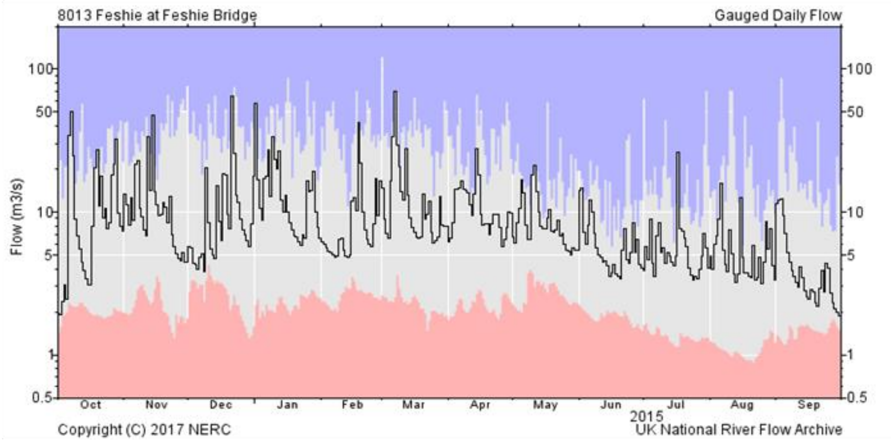
8013 Feshie at Feshie Bridge
Gauged Daily Flow
Flow (m3/s)
100
50
10
5
1
0.5
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
2013
Copyright (C) 2017 NERC
UK National River Flow Archive

b)



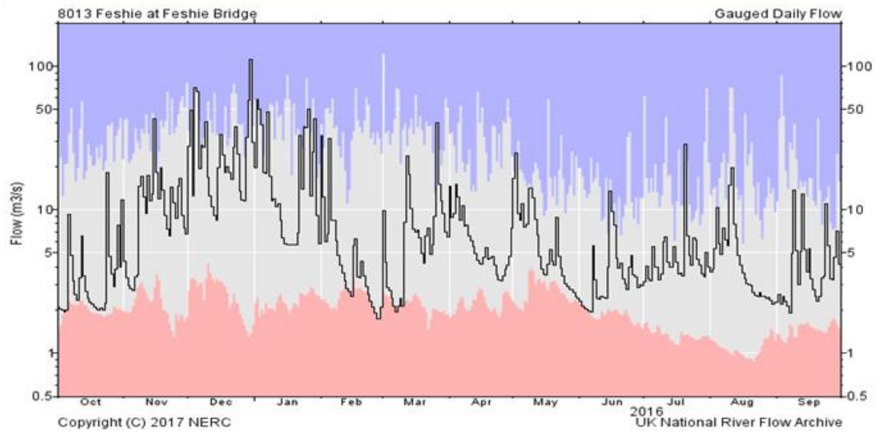
8013 Feshie at Feshie Bridge
Gauged Daily Flow
Flow (m3/s)
100
50
10
5
1
0.5
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
2014
Copyright (C) 2017 NERC
UK National River Flow Archive

c)



8013 Feshie at Feshie Bridge
Gauged Daily Flow
Flow (m3/s)
100
50
10
5
1
0.5
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
2015
Copyright (C) 2017 NERC
UK National River Flow Archive

d)



8013 Feshie at Feshie Bridge
Gauged Daily Flow
Flow (m3/s)
100
50
10
5
1
0.5
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
2016
Copyright (C) 2017 NERC
UK National River Flow Archive

Figure 5-6: Feshie Bridge daily flow hydrographs

Annual hydrographs showing the rate of flow at Feshie Bridge Gauging Station for: water years 2012/13 (a), 2013/14 (b) and 2014/15 (c) and 2015/16 (d) (National River Flow Archive, 2017). Black line displays the daily flow and the blue and red correspond with the max and min daily flows respectively. Note that the hydrological water year begins on October 1st to take account of the precipitation falling in autumn/winter that accumulates as snow and melts the following spring.

5.2.4.1 River Feshie annual runoff

The annual runoff values (Section 4.5.1.1) for the River Feshie were calculated for the water years covering the four year study period (2012-2016) using the mean flow values ranging from 5.87 to 9.58 m^3 s^{-1} (Section 5.2.4) and the catchment area of 231 km^2 (Section 5.2.1). The total depth of runoff for the Feshie catchment varied from 801 – 1308 mm (Table 5-1). Mean annual precipitation for the River Feshie was around 1273 mm, typical evapotranspiration from the area should be in the region of 226 mm per annum. Therefore, this indicates that the annual runoff from the land is likely to be approximately 1047 mm (Marsh and Hannaford, 2008). The annual runoff values calculated for the River Feshie are further supported by Soulsby and colleagues (1997) who reported 1100 mm estimated mean annual precipitation in the Allt a' Mharcaidh, with up to 30 % falling as snow.

Across the wider dataset (1993-2016), the mean annual catchment runoff values can be used as a catchment descriptor for the Feshie valley. The mean annual flow measured at the Feshie Bridge gauging station (7.78 m^3 s^{-1}) is equivalent to the notional depth of water over the catchment (1062 mm).

Table 5-1: Annual runoff for the River Feshie

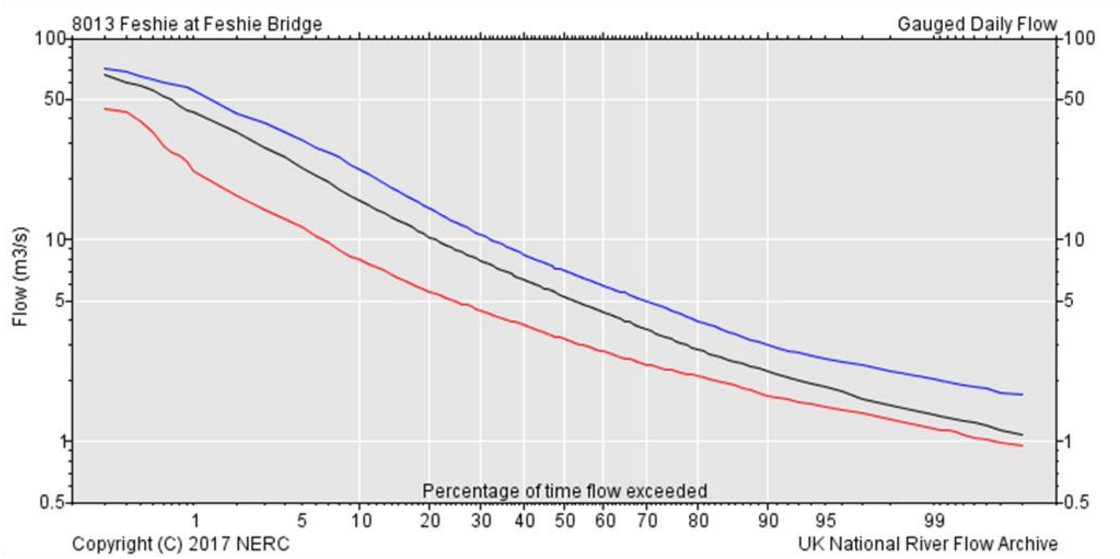
Annual runoff was calculated for water years that cover the duration of the project, note that the hydrological water year begins on October 1st. The River Feshie daily flow values used to calculate the mean flow per annum were taken from the NRFA (2017).

Water Year	Annual Runoff (mm)
2012/13	801
2013/14	1177
2014/15	1308
2015/16	1269

5.2.5 Flow duration curve

A flow duration curve (FDC), as provided in Figure 5-7 is a useful way of summarising the flow characteristics of a river. The flow is referred to in relation to an exceedance probability x as Q(x). The percentage of time flow is exceeded above Q10 is considered high flow rates. Flow rates from Q10 – Q90 are considered 'normal flows' and less than Q90 as low flows. The River Feshie drains from upland streams and the FDC has quite a steep gradient representing a relatively 'flashy' flow regime reflecting the range of flows experienced from extreme highs to low flows from the streams (Figure 5-7a). For comparisons, the River Avon (Spey) FDC (Figure 5-7b) has a slightly more stable flow regime when compared with the steeper lines of River Feshie FDC.

a)



b)

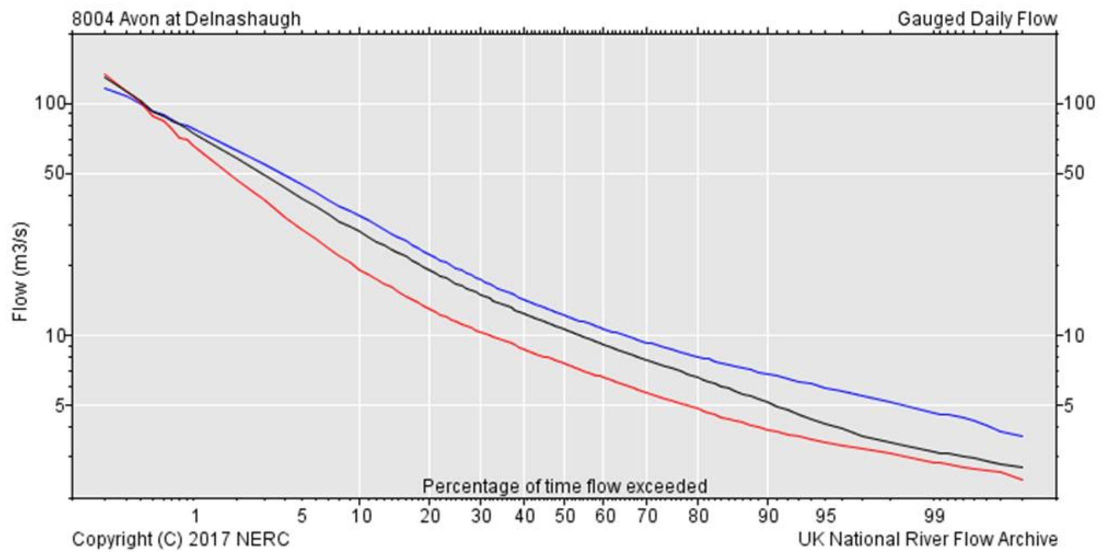


Figure 5-7: Flow duration curves

For the River Feshie at Feshie Bridge (a) in comparison to the River Avon at Delnashaugh (b). On both graphs, the total mean annual flow is shown in black. The winter flow rates from December to March are shown in blue and the summer flow rates from June to September are shown in red. For the River Feshie: the flow percentages of 10 % exceedance (Q10) = 15.69 $m^3\ s^{-1}$, Q50 = 5.266 m^3/s, Q70 = 3.587 $m^3\ s^{-1}$and Q95 = 1.875 $m^3\ s^{-1}$. Mean flow = 7.819 $m^3\ s^{-1}$, BFI = 0.49, percent complete = 96 %, period of record: from 1992 – 2016 (National River Flow Archive, 2017). For comparison a flow duration curve for another of the Spey's tributaries, the River Avon is shown. The Avon drains a larger catchment area (543 km^2 versus 231 km^2) but it displays a less flashy nature (gradient of line slightly less steep) when compared with the River Feshie. This is reflected in the BFI of 0.55 for the River Avon (National River Flow Archive, 2017).

5.2.6 Baseflow Index

The Baseflow Index (BFI) is a method used to measure the ratio of runoff from stored sources and the contribution of groundwater to river flow, for indexing the effect of geology on low flows. The BFI ranges from 0.1 for a very flashy river to >0.9 for a very stable river. Variations in geologies can result in different BFIs such as, impermeable (low BFI e.g. clay) to permeable (high BFI e.g. chalk). For this study, the BFI of the River Feshie sits in the middle (0.49). Mountain, heath and bog make up 83 % of the catchment land cover of the Feshie. The bedrock geology of the upper reaches of the River Feshie inclusive of the study site is comprised of Gaick Psammite formation and the lower reaches comprise of Loch Laggan Psammite formation. These are sedimentary rocks, possibly of marine origin that have subsequently undergone metamorphism. The aquifer productivity including the upper and the lower reaches of the River Feshie is mapped as low in productivity. This indicates that virtually all flow is moving through fractures and other discontinuities. It is also predicted that a small amount of groundwater may be evident in near surface weathered zones and secondary fractures (O Dochartaigh *et al.*, 2015).

5.2.7 River Feshie summary

Over the study period between 2013 and 2016, a comparable lowest (January 2016) and highest (December 2015) water levels since monitoring began in 1992 have been recorded indicating an interesting study period of two extremes. It was also interesting to observe the differences in response times represented by the hydrographs, where the rise in peak flow as a result of a rainfall or snowmelt event took from four to twelve days to occur. A comparison can be made as to how the response times vary from the headwater study streams monitored in this study. Here, it was expected that the peak flows would occur much sooner. The ranges of flows have been from extreme highs to low flows and are predominately affected by the snow cover in the catchment in the corresponding years.

The estimated mean annual catchment runoff values for the study period sit within the long term mean of 1062 mm, whereby 2012/13 was lower and 2013/16 were higher. The River Feshie is a braided channel system inclusive of debris cones, river terraces and alluvial fans with the steep glen surrounding the catchment area meaning a relatively ‘flashy’ flow regime is typical for the River Feshie. There appears to be quite a large range of flows recorded in response to climatic conditions over the monitored years (5.87 to 9.58 $m^3 s^{-1}$), it will be useful to compare if the same pattern of response is noted within the upper catchment.

5.3 Mòine Mhór stream levels and flow rates

5.3.1 Location

The Mòine Mhór streams are positioned in the upper catchment reaches of the River Feshie. The condition and response of these headwater streams impacts on the wider Spey catchment area and may have implications further downstream for events such as flooding. The Spey has historical evidence of recurring flooding at Kingston and Garmouth which are located within the Spey Bay Potentially Vulnerable Area for river and coastal flooding (Scottish Environment Protection Agency, 2015). Water level and flow data was collected for all the streams draining from the study catchment of the Mòine Mhór. This study is at a smaller spatial scale to the wider catchment area of the River Feshie but it represents an intensively monitored upland catchment. The importance of collecting data from upland headwater streams was discussed in Section 2.3 and the challenges associated with it have been described by others (Section 2.3.5) and indicated with reference to this particular study site in Section 4.15.

5.3.2 Stream levels

HOBO data loggers were used to record water pressure and temperature at the eight monitored streams on the Mòine Mhór plateau as described in Section 4.3.1 over a three year period. Figure 5-8 displays the derived level data and water temperature recorded at each of the monitored streams. Table 5-2 summarises any data gaps present and highlights the completeness of the dataset across the study period.

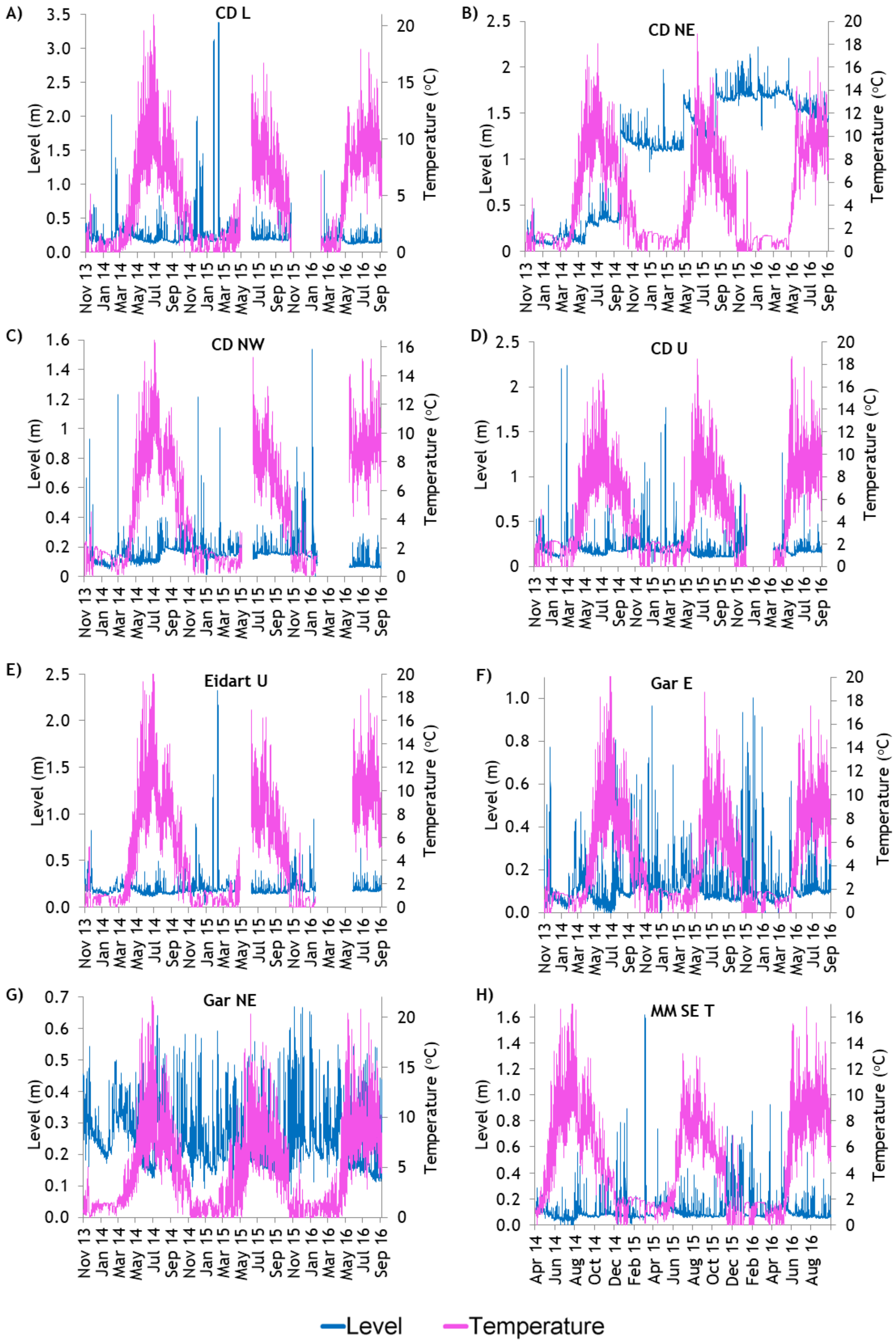


Figure 5-8: Stream level and stream temperature for the monitored streams

Level shown in blue was calculated by correcting the pressure recorded on the HOBO data logger with an atmospheric barometric logger initially located at Feshie Bridge from 19th November 2013 to 29th August 2014 and then on the plateau at the same altitude from 29th August 2014 to 30th

September 2016. All loggers were set to record data at 15-minute intervals. Data shown for; CD L (A), CD NE (B), CD NW (C), CD U (D), Eidart U (E), Gar E (F), Gar NE (G) and MM SE T (H). A gap exists in CD L (A) data from the 17th November 2015 up to the 1st March 2016 this was caused by removing the HOBO from study site due to an error when downloading it in the field. It was unsuccessfully redeployed on the next study site visit due to snow cover however; a temporary site was used from 1st March 2016 until 7th July 2016. On 7th July 2016 the CD L HOBO was installed at a new location ~ 5 m downstream of old location due to bank collapse. Data gaps have been summarised below in Table 5-2. Note the CD NE site (B) was excluded due to suspicious step changes in the level of over 1 m which would not have been realistic in a small tributary. Temperature of the stream shown in pink shows a seasonal variation with the upper limits similar across the monitored streams.

Table 5-2: Completeness of HOBO data loggers for the monitored streams

Where gaps have been observed in Figure 5-8 above, the timings and reasons are clarified. Note the MM SE T was added to the network at a later date and started logging on the 1st of April 2014 up until the 30th of September 2016. All other data loggers cover the study period from November 2013 to 30th of September 2016. Some unsuccessful attempts were made to dig out the HOBOs for download during snow cover and are the reason for many of the gaps outlined below.

Monitored stream	Data gap period	Days	Reason	Completeness of dataset (%)
CD L	23/05/15 - 02/07/15	40	Unable to access due to snow cover	86
	17/11/15 - 01/03/16	105	Removed from site due to an error when downloading in the field and was unsuccessfully re-deployed on next site visit due to snow cover	
CD NE	None		N/A	100
CD NW	23/05/15 - 02/07/15	40	Unable to access due to snow cover	85
	13/02/16 - 03/06/16	111		
CD U	26/12/15 - 30/03/16	95	Unable to access due to snow cover	91
Eidart U	24/05/15 - 02/07/15	39	Unable to access due to snow cover	84
	13/02/16 - 21/06/16	129	Unable to access due to snow cover	
Gar E	None	N/A	N/A	100
Gar NE	None	N/A	N/A	100
MM SE T	None	N/A	N/A	100

A variation in level was recorded across the years and when comparing the monitored streams against each other (Figure 5-8). As may be expected, the Caochan Dubh (upper monitored location and lower monitored location) was the largest stream draining the Mòine Mhór and recorded the largest peaks in level. The Caochan Dubh lower site was fed by the Caochan Dubh upper (which was part of the same stream), the tributaries (Caochan Dubh north east and Caochan Dubh north west) as well as the Mòine Mhór south east tributary. It appears that the Garbhlach east, which has a greater eroded area in comparison to the adjacent catchment (Table 4-1), was more responsive to events than the Garbhlach north east.

In Figure 5-8 it can be noted that the Mòine Mhór south east tributary started recording at a later date (1st April 2014) in comparison to the other locations (19th November 2013). This was due to scoping out a suitable location for another instrument (the spectro::lyser, discussed in section 5.7) and the Mòine Mhór south east tributary was decided as the best suited location. The Mòine Mhór south east tributary was then added to the monitoring network at this stage. The Mòine Mhór south east tributary is located in a central position on the plateau and has a spread in stream levels recorded across the time series. The Eidart upper appears to flow at a fairly steady level throughout however some high level events were recorded with a peak in level of 2.3 m on 7th March 2015. The other monitored streams also experienced this increase in level on the 7th March 2015 which is noted during a period of cold water temperatures that are close to zero. A site visit on the 27th March 2015 confirmed the site was still snow covered. Upon analysis of the data, one of the monitored streams was excluded, the Caochan Dubh north east, due to the unexpected level jumps. It was observed that the HOBO was placed in a small tributary where the bed material was mobile and channel shape change was experienced and this may have contributed to the unreliable data gathered. The HOBO was also noted to be encased and buried in sediment upon each visit which may have further contributed to the unrealistic jumps in water level of 1 m between download periods.

5.3.3 Stream temperatures

Variations in the spatial and temporal stream thermal regime can have significant impacts on the chemical and ecological water quality and in water resources available downstream (Langan *et al.*, 2001). Stream temperature data has been graphed on a secondary axis alongside the level data (Figure 5-8). The maximum upper limit of stream temperature of 20 °C was recorded at Caochan Dubh lower, Caochan Dubh north east, Caochan Dubh upper, Eidart upper, Garbhlach east and Garbhlach north east. The upper limit of stream temperature of 16 °C was recorded at Caochan Dubh north west and Mòine Mhór south east tributary. Across the locations, stream temperatures on the whole were close to zero from November through to April. The temperature then starts to rise, reaching its peak around July before falling again and repeating the yearly cycle. For around six months of the year the stream temperature is at freezing reflecting the high altitude and arctic-alpine environment of the Mòine Mhór. In relation to the seasons, the spring snow melt around May sees a corresponding rise in stream temperatures annually. To explore in more detail, the annual means for the reported results on stream temperature have been collated in Table 5-3.

Table 5-3: Annual mean stream water temperature in the monitored catchments covering from 2013-2016

HOBOs were placed in the eight monitored stream (fully submerged) and recorded stream temperature at 15-minute intervals in units of degrees Celsius (˚C). Temperatures are a mean of all the 15-minute values measured throughout each year.

Stream	Mean Annual Temperature (˚C)			
	2013	2014	2015	2016
CD L	0.72*	4.52	3.75*	5.82*
CD NE	1.20*	4.64	3.73	4.77*
CD NW	1.60*	4.72	3.53	6.76*
CD U	1.36*	4.73	3.86	6.54*
Eidart U	0.75*	4.60	3.31	6.82*
Gar E	1.30*	4.57	3.56	4.66*
Gar NE	1.29*	4.50	3.84	4.84*
MM SE T	-	5.72*	3.59	4.63*

Data based on 365 days unless specified, a * indicates an incomplete year: 2013 data only covers 42 days, MM SE T 2014 (274 days data), CD L 2015 (320 days data), CD L 2016 (213 days data), CD U 2016 (184 days data) and all other 2016 sites (273 days data)

To assess changes within the monitored years, the seasonal mean for the reported results on stream temperatures have been collated in Table 5-4. In terms of complete data sets, the calculated mean stream temperature on the Mòine Mhór for spring, summer, autumn and winter was 2.42, 8.71, 8.14 and 1.13 ˚C respectively. The low temperatures of winter and spring highlight the arctic-alpine environment of the study site. Snow remains on the study site until the early summer months, keeping the stream temperatures low for around half of the year.

Table 5-4: Annual and seasonal mean stream water temperature in the monitored catchments covering from 2013-2016

The seasons were split up into spring (April – May), summer (June – August), autumn (September – November) and winter (December – March) to reflect the arctic-alpine montane environment of the Mòine Mhór plateau.

		Temperature (^{o}C)			
Stream		Spring	Summer	Autumn	Winter
CD L	2013	-	-	0.36*	0.60
	2014	3.26	9.47	5.65	0.63
	2015	1.18[+]	8.57^	5.36[>]	0.68[#]
	2016	2.11	9.03	8.85[<]	-
CD NE	2013	-	-	0.99*	1.15
	2014	3.04	9.42	5.61	1.13
	2015	1.23	8.08	4.57	0.89
	2016	1.82	9.21	8.90[<]	-
CD NW	2013	-	-	1.51*	1.42
	2014	3.25	9.06	5.71	1.38
	2015	0.96[+]	8.45^	4.74	1.16~
	2016	-	8.83	8.76[<]	-
CD U	2013	-	-	0.96*	1.63
	2014	4.08	8.72	5.39	1.45
	2015	1.54	7.73	4.56	1.11**
	2016	2.20	8.90	8.46[<]	-
Eidart U	2013	-	-	0.39*	0.78
	2014	2.93	9.75	5.74	0.65
	2015	0.74[+]	8.80^	4.66	0.45[=]
	2016	-	9.77	9.21[<]	-
Gar E	2013	-	-	1.07*	1.37
	2014	3.02	8.99	5.43	1.43
	2015	1.34	7.14	4.38	1.17
	2016	2.00	8.59	8.42[<]	-
Gar NE	2013	-	-	1.18*	1.18
	2014	2.99	8.88	5.63	0.94
	2015	2.18	7.84	4.70	0.96
	2016	2.65	9.00	8.52[<]	-
MM SE T	2013	-	-	-	-
	2014	3.14	8.90	5.67	1.56
	2015	1.29	6.94	4.64	1.08
	2016	1.96	8.60	8.42[<]	-

* Based on 11 days data, HOBOs installed on 19 Nov 2013
+ Based on 52 days data ^ Based on 60 days data
> Based on 77 days data = Based on 74 days data
** Based on 26 days data ~ Based on 74 days data
# Based on 30 days data < Based on 29 days data

The level was corrected for atmospheric pressure using a HOBO, which was located outside of the water and exposed to the air. This HOBO recorded temperature alongside pressure. Graphs were produced to show the relationship between air temperature and stream temperature (Figure 5-9 and Figure 5-10).

At the start of the project, air temperature was taken from an atmospheric HOBO located at a lower altitude (Feshiebridge). At a later date a second atmospheric HOBO was deployed on the study site, at the same altitude and in closer proximity to the HOBOs recording stream temperature. Two figures have been created to distinguish between the two locations at which air temperature was recorded due to the differences in location and altitude (Section 4.3.4).

A regression equation describing the relationship of stream water temperature and air temperature was derived in Excel and is shown alongside the r^2 value in Figure 5-9 and Figure 5-10. A regression line of 0.50 is generally regarded as a good fit to the data and 0.75 and above is regarded as a very good fit to the data. For the Feshiebridge temperatures, between 62 and 71 % of the variation in y is accounted for by the fitted regression line. For the Mòine Mhór temperatures, between 64 and 77 % of the variation in y is accounted for by the fitted regression line. The fit has improved slightly which would be expected when the atmospheric HOBO was located at a similar altitude and in closer proximity to the monitored streams. At both locations, the lowest fit was recorded at the site that was installed at a later date to the others, the Mòine Mhór south east tributary, the smaller dataset may account for the lower r^2 values achieved.

As expected, the air temperature appears more variable and responsive to the changing seasons and generally higher when compared with the stream temperature. Throughout the winter months the stream temperature remains around 0 °C whereas the air temperature drops below these freezing temperatures.

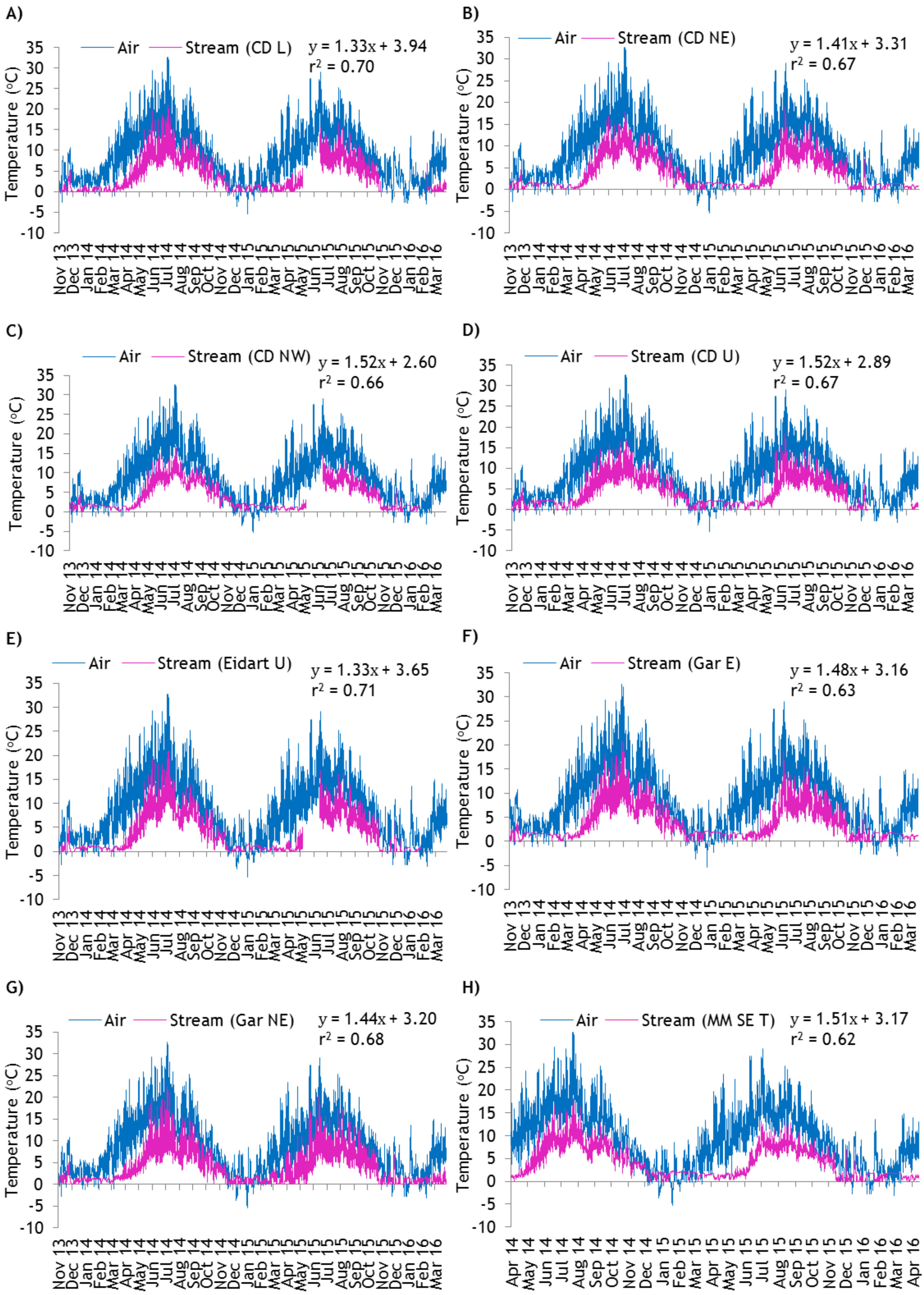


Figure 5-9: Relationship between air temperature and stream temperature (Nov 2013 – Mar 2016)

When placed at different altitudes and locations the relationship between air temperature (blue) and stream temperature (pink) is displayed. The stream temperature was derived from the HOBOs situated on the Mòine Mhór and the air temperature was derived from an atmospheric HOBO situated at Feshiebridge at the lower altitude of 232 m. The graphs show the regression equation and r^2 value for each of the monitored streams.

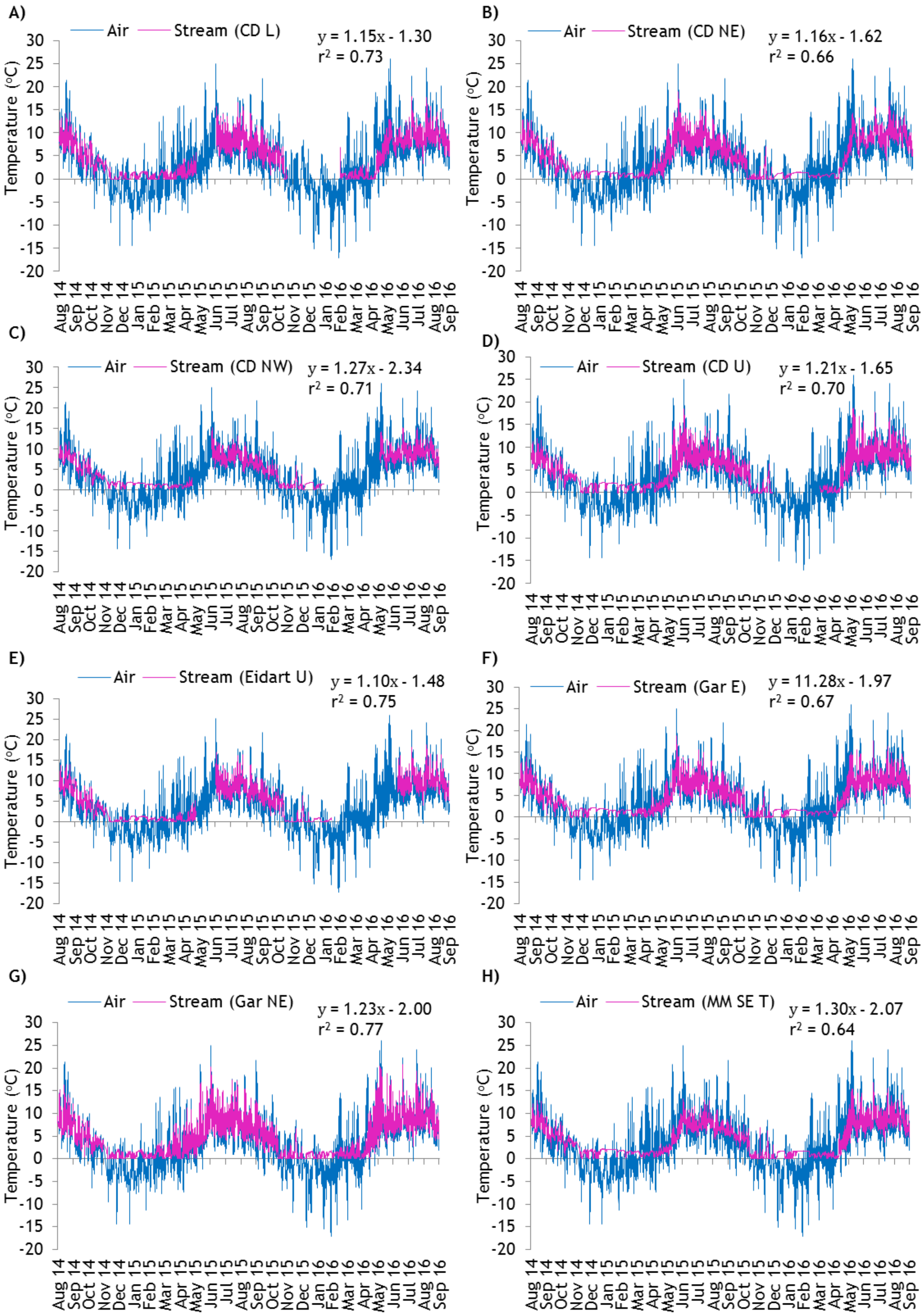


Figure 5-10: Relationship between air temperature and stream temperature (Aug 2014 – Sept 2016)

When placed at similar altitudes and locations the relationship between air temperature (blue) and stream temperature (pink) is displayed. The stream temperature was derived from the HOBO and the air temperature was derived from an atmospheric HOBO situated on the Mòine Mhór at the same altitude (914 m). The graphs show the regression equation and r^2 value for each of the monitored streams.

In summary, the air temperature appears more responsive to a wider range of changes in the maximum and minimum values for air temperature in comparison to the stream temperature (Figure 5-9 and Figure 5-10). However, the relationship and response of the water to the air temperature is evident throughout the year inclusive of when the stream is snow covered. There is a slight breakdown in the relationship between water and air temperature in the winter months as the stream was insulated by snow. The increase in stream temperature in line with spring water contributions is also evident in the improvement of fit between water and air temperatures in the spring through to autumnal months. The mean annual stream temperatures for the complete years monitored was around 3-4 °C. Overall, marginally higher r^2 values were achieved (0.64 to 0.77) when the atmospheric barometric unit was placed on the Mòine Mhór (Figure 5-10), highlighting the importance of monitoring atmospheric pressure at the same location as the stream level. The collection of this dataset also highlighted the difficulties of siting the loggers within this environment. The Caochan Dubh north east yielded an unrealistic level dataset for the catchment size which may be reflective of the mobile channel and amount of sediment the sensor would become encased in. The seasonal peaks in air and stream temperature are evident throughout the years and indicate a repeating pattern year on year with small scale variability. The level data is more variable between years with differences in peaks and baseflow level occurring between and within the monitored streams (Figure 5-8). Converting the level data into a flow of water will help to further understand the patterns emerging between the years and streams.

5.3.4 Flow rate in the Mòine Mhór streams

In addition to continuously monitoring stream level and stream temperature at 15-minute intervals by use of HOBO data loggers, across the duration of the project, as highlighted in Section 5.2.2, level data can be used to calculate flows in the river. Before the level data could be converted to flow, a quality assurance (QA) check of the level data was compared against the observed water level readings taken during field visits (Figure 4-3). These were compared with the field gauging results for flow (Section 4.5) and used to create the flow ratings curves for each of the monitored streams. The results have been presented for all field gaugings and for a select few gaugings following checks to try improve the fit and create a more realistic flow data set for the monitored streams. For direct comparison, the ratings have been displayed on the same graph (Figure 5-11). The justification for this is outlined in more detail below.

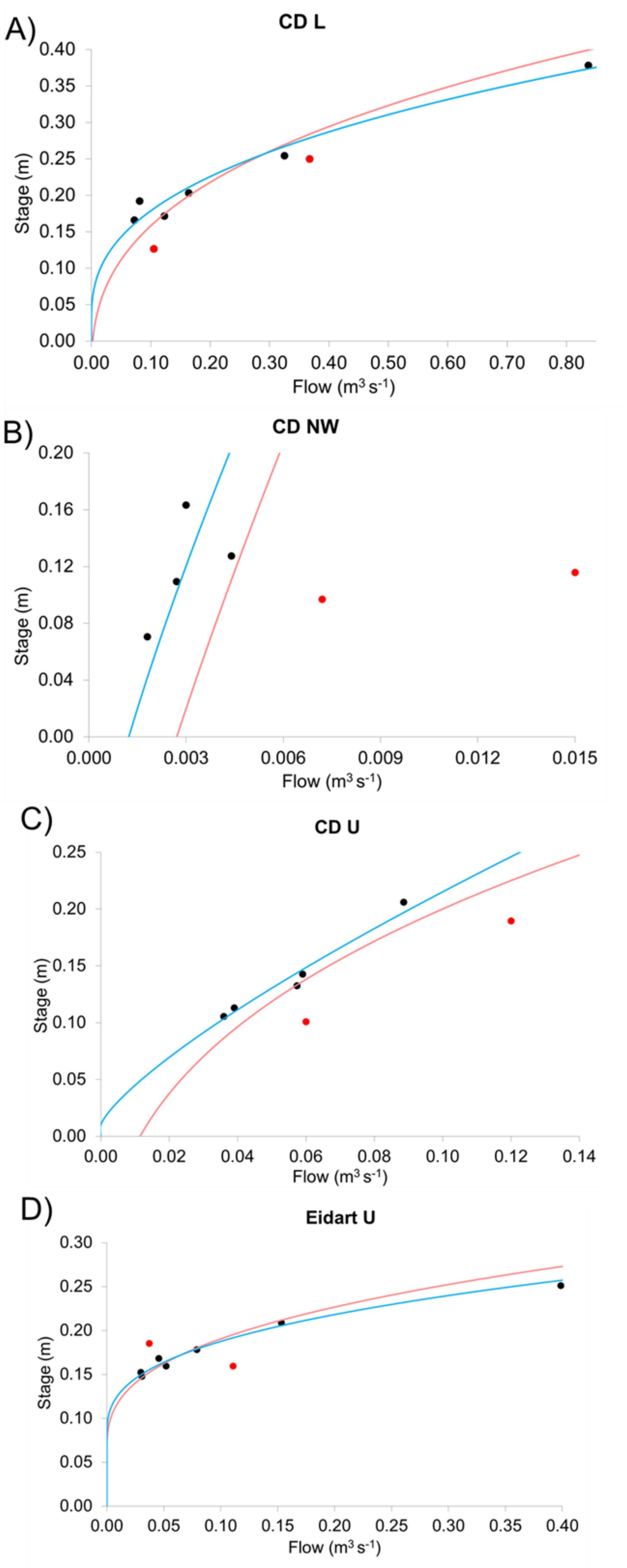
Initially, all gaugings were used to create the rating curves for the monitored streams. The stage values were taken from the logged level (HOBO logger) and the flow rates from the gaugings carried out (Table 4-8). HYDATA software was used to fit the rating curve to a power function. The output of information from the fit created by the HYDATA software included a, b and c values (Equation 4-7) which were then input into Excel. As previously mentioned in Section 4.5.1, the equation was then used to derive a continuous dataset for flow, a process which was repeated across the seven monitored catchments.

It was decided that to create a better fit and due to having a cluster of gaugings all around the same level, the most reliable and realistic ones were chosen as part of the QA process and the analysis was re-run and output a new equation from which flow was derived (Section 4.5.1). A justification for the gaugings excluded at each of the monitored locations is presented below in Table 5-5.

Table 5-5: Justification for exclusion of gaugings from rating curves to improve fit

Stream	Gauging date/time	Stage (m)	Flow (m^3 s^{-1})	Justification for exclusion
CD L	08/05/14 13:45	0.250	0.367	Snow covered ground, preferred comparable gauging
	21/06/16 11:15	0.126	0.105	Preferred comparable cluster of gaugings from 2014/15 selected
CD NW	08/05/14 13:30	0.116	0.015	Snow covered ground, low confidence in gauging, preferred comparable cluster of gaugings
	15/05/14 16:15	0.097	0.007	Snow covered ground, low confidence in gauging, preferred comparable cluster of gaugings
CD U	15/05/14 17:00	0.189	0.120	Snow covered ground, preferred comparable gauging
	06/07/15 11:30	0.101	0.060	Low flows, preferred comparable gauging
Eidart U	09/09/15 09:45	0.160	0.111	Wet conditions, resulted in overestimation of flows, excluded
	21/06/16 08:45	0.185	0.037	Preferred comparable cluster of gaugings from 2014/15 selected
Gar E	09/07/14 13:00	0.050	0.026	Low flows, preferred cluster of comparable gaugings
	21/06/16 15:00	0.088	0.019	Low flows, preferred cluster of comparable gaugings
Gar NE	15/05/14 11:00	0.311	0.282	Snow covered ground, preferred comparable gauging
	21/06/16 15:45	0.158	0.011	Low flows, preferred comparable cluster of gaugings
MM SE T	23/08/14 09:15	0.097	0.009	Low flows, preferred comparable gauging, lower confidence in gauging as flow meter ran out of battery (rotations counted by eye)
	04/09/14 13:30	0.073	0.023	Preferred cluster of comparable gaugings
	11/09/15 14:30	0.071	0.018	Preferred cluster of comparable gaugings
	28/10/15 15:30	0.062	0.014	Preferred cluster of comparable gaugings
	03/06/16 12:30	0083	0.023	Preferred cluster of comparable gaugings

The rating curves created with all gaugings produced higher flow estimates compared to the selected gauging curves for the Caochan Dubh north west, Caochan Dubh upper and Garbhlach north east. Although an improvement in fit and a reduction in flow were achieved by selectively removing some of the gaugings, an overestimation in runoff in comparison to the River Feshie was still observed. In contrast for the Caochan Dubh lower, Eidart upper, Garbhlach east and Mòine Mhór south east tributary, the rating curves created with all gaugings resulted in a reduced annual runoff rate when compared to the selected gauging option. However, for both options it is noted that there is low confidence in the flow data produced. All the estimated flows (apart from the Caochan Dubh north west) produce higher runoff rates when compared with the annual precipitation of 1275 mm and the River Feshie runoff rate of 801-1308 mm (Section 5.2.4.1). The Caochan Dubh north west and Caochan Dubh upper sites were the only two sites that were close to this range of values. To demonstrate the numbers and for comparison purposes, the equations used to calculate flows with all gaugings and the selected gaugings equations used to calculate flow have been carried through to Section 5.3.5 (daily flow) and Section 5.3.6 (annual runoff).


A)
CD L
Stage (m)
Flow (m3 s-1)
B)
CD NW
Stage (m)
Flow (m3 s-1)
C)
CD U
Stage (m)
Flow (m3 s-1)
D)
Eidart U
Stage (m)
Flow (m3 s-1)

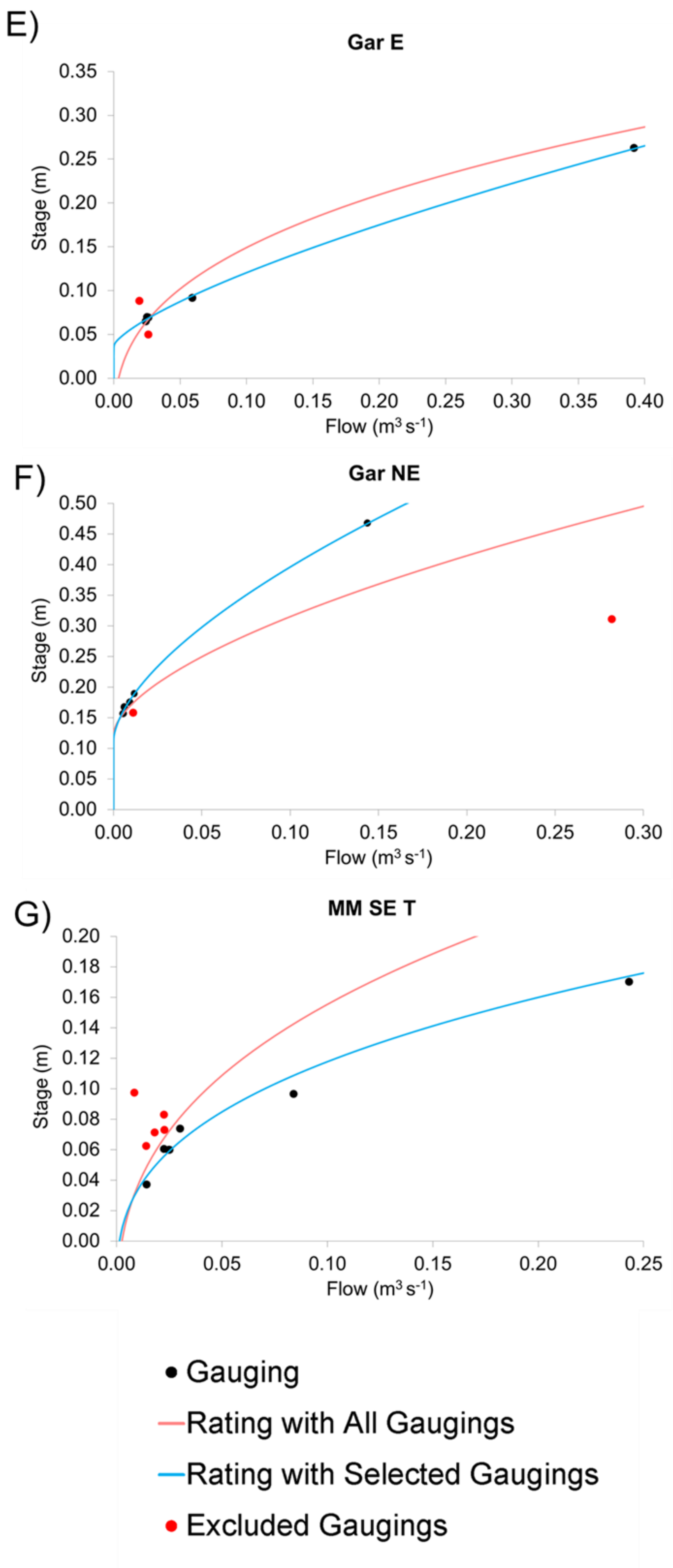

E)
Gar E
Stage (m)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40
Flow ($m^3 s^{-1}$)
F)
Gar NE
Stage (m)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00 0.05 0.10 0.15 0.20 0.25 0.30
Flow ($m^3 s^{-1}$)
G)
MM SE T
Stage (m)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.00 0.05 0.10 0.15 0.20 0.25
Flow ($m^3 s^{-1}$)
Gauging
Rating with All Gaugings
Rating with Selected Gaugings
Excluded Gaugings

Figure 5-11: Rating curves for the monitored streams on the Mòine Mhór

The graphs were created in Excel and are shown above for the CD L (A), CD NW (B), CD U (C), Eidart U (D), Gar E (E), Gar NE (F) and MM SE T (G). Stage is shown on the y-axis and flow ($m^3 s^{-1}$) on the x-axis. The rating curve is shown using all flow gaugings (red line) and for the selected gaugings (blue line) used to create the flow rating equation as outputted by HYDATA. The black dots show the utilised gaugings and the red dots display the excluded gaugings. Gaugings were excluded on a site by site basis based on numerous flows at the same level or unrealistic values obtained.

Using the selected gaugings the final rating equations calculated with HYDATA were defined from water level in metres (h) and flow in $m^3 s^{-1}$ (Q) and are as follows:

	Q = a (h + c) ^ b	
CD L:	Q = 12.779 (h - 0.027) ^ 2.570	Error of fit: 0.124
CD NW:	Q = 0.019 (h + 0.122) ^ 1.300	Error of fit: 0.108
CD U:	Q = 0.784 (h- 0.010) ^ 1.300	Error of fit: 0.034
Eidart U:	Q = 49.944 (h - 0.079) ^ 2.800	Error of fit: 0.070
Gar E:	Q = 3.058 (h - 0.037) ^ 1.376	Error of fit: 0.036
Gar NE:	Q = 0.776 (h – 0.114) ^ 1.376	Error of fit: 0.041
MM SE T:	Q = 20.175 (h + 0.033) ^ 2.800	Error of fit: 0.085

Equation 5-1: Rating curve equations for monitored streams with selected gaugings

For comparison, the reduced error of fit is evident from the rating curve equations created with all gaugings:

	Q = a (h + c) ^ b	
CD L:	Q = 7.655 (h + 0.054) ^ 2.800	Error of fit: 0.173
CD NW:	Q = 0.017 (h + 0.245) ^ 1.300	Error of fit: 0.351
CD U:	Q = 1.599 (h + 0.172) ^ 2.800	Error of fit: 0.108
Eidart U:	Q = 31.090 (h - 0.062) ^ 2.800	Error of fit: 0.216
Gar E:	Q = 7.417 (h + 0.066) ^ 2.800	Error of fit: 0.177
Gar NE:	Q = 1.547 (h - 0.123) ^ 1.658	Error of fit: 0.292
MM SE T:	Q = 7.625 (h + 0.057) ^ 2.800	Error of fit: 0.271

Note: these values are shown for comparison purposes

Equation 5-2: **Rating curve equations for monitored streams with all gaugings**

Ideally, more gaugings would have been carried out to increase the accuracy of the rating curves and reduce the error of fit. However, this was as many as practically possible throughout the project timeline. The snow covered streams meant that gauging during the winter period was a rare occurrence although some were conducted and are thus valuable in terms of understanding what is happening to the stream during these periods. Access constraints, in terms of a bridge being washed away, made it difficult to access the plateau safely during high events. The only option was to walk in on foot from a footbridge located 5 km downstream which was challenging due to the distance and nature of the weather conditions during these events. The small number of high river level flow gaugings that were successfully managed are important for understanding the stream response during these events. However, it is acknowledged that there is an error associated with the creation of the flow values given the limitations that existed with collecting further higher gaugings.

Flow was calculated from the ratings equations outlined above. The mean flow across the years and between the monitored streams is shown in Table 5-6. The values reported are lower than the mean flow for the River Feshie (7.751 m^3 s^{-1}), which is to be expected as the flow increases as the water moves downstream with increasing catchment and channel size. The largest flows are recorded in the Eidart upper and Caochan Dubh lower which would again be expected as these streams have the largest catchment areas in comparison to the other monitored streams. In general, a direct correlation is observed where increasing catchment area alongside the width and depth of the channel results in flow increases.

Table 5-6: Flow for the monitored streams across the years

The mean flows are based on the 15-minute calculated flow values before any abnormal peaks were removed to give an indication of the completeness of the dataset across the study period. The flows were calculated using the selected gaugings rating curve (Equation 5-1). No data available for CD L in 2016 due to bank collapse and movement of gauging station.

Stream	Dates based on	Days missing	Year	Mean flow ($m^3\ s^{-1}$)
CD L	26/11/2013 – 31/12/2013	0	2013	0.460
	01/01/2014 – 31/12/2014	0	2014	0.654
	01/01/2015 – 28/10/2015	38	2015	3.143
CD NW	26/11/2013 – 31/12/2013	0	2013	0.003
	01/01/2014 – 31/12/2014	0	2014	0.003
	01/01/2015 – 31/12/2015	38	2015	0.004
	01/01/2016 – 30/09/2016	109	2016	0.003
CD U	26/11/2013 – 31/12/2013	0	2013	0.116
	01/01/2014 – 31/12/2014	0	2014	0.108
	01/01/2015 – 26/12/2015	0	2015	0.099
	30/03/2016 – 30/09/2016	0	2016	0.088
Eidart U	26/11/2013 – 31/12/12013	0	2013	0.621
	01/01/2014 – 31/12/2014	0	2014	0.148
	01/01/2015 - 31/12/2015	37	2015	1.466
	01/01/2016 – 30/09/2016	127	2016	0.263
Gar E	26/11/2013 – 31/12/2013	0	2013	0.121
	01/01/2014 – 31/12/2014	0	2014	0.101
	01/01/2015 – 31/12/2015	0	2015	0.147
	01/01/2016 – 30/09/2016	1	2016	0.100
Gar NE	26/11/2013 – 31/12/2013	0	2013	0.055
	01/01/2014 – 31/12/2014	0	2014	0.034
	01/01/2015 – 31/12/2015	0	2015	0.029
	01/01/2016 – 30/09/2016	0	2016	0.027
MM SE T	01/04/2014 – 31/12/2014	0	2014	0.149
	01/01/2015 – 31/12/2015	0	2015	0.532
	01/01/2016 – 30/09/2016	1	2016	0.233

To summarise, it is acknowledged that limitations exist with reference to the rating curves (Figure 5-11) however, by selecting the most applicable gaugings, equations for each monitored stream have been derived. These equations allowed the corresponding flow within each stream to be calculated with greater confidence. The new mean flow values appear believable (Table 5-6) compared with what would be an expected flow of the streams (photograph of stream channel in Figure 4-2). The next stage of the analysis, given that some of the high peaks were experienced during the winter months and to reduce the volume of the dataset was to summarise the values to give a daily mean flow.

5.3.5 Daily flow data

More commonly, statistics are derived from the daily flow data hence the conversion from the high resolution 15-minute interval data presented in summary format in Table 5-6. The 15-minute flow data was used to calculate the mean gauged daily flow to produce a time series of daily measured river flow for the monitored streams. These have been calculated for a calendar day and allow for the data to be presented as a graphical output (Figure 5-12 and zoomed in Figure 5-14). Suspect data has been highlighted within the graphs and includes anomalous values. The periods marked as suspect predominately occur during the winter months from a period inclusive of November through to February. During these months, the HOBOs were covered by snowpack rather than melt events, reducing the certainty in the data collected. Figure 5-12 and Figure 5-14 display the daily mean flow across the years for each of the monitored streams.

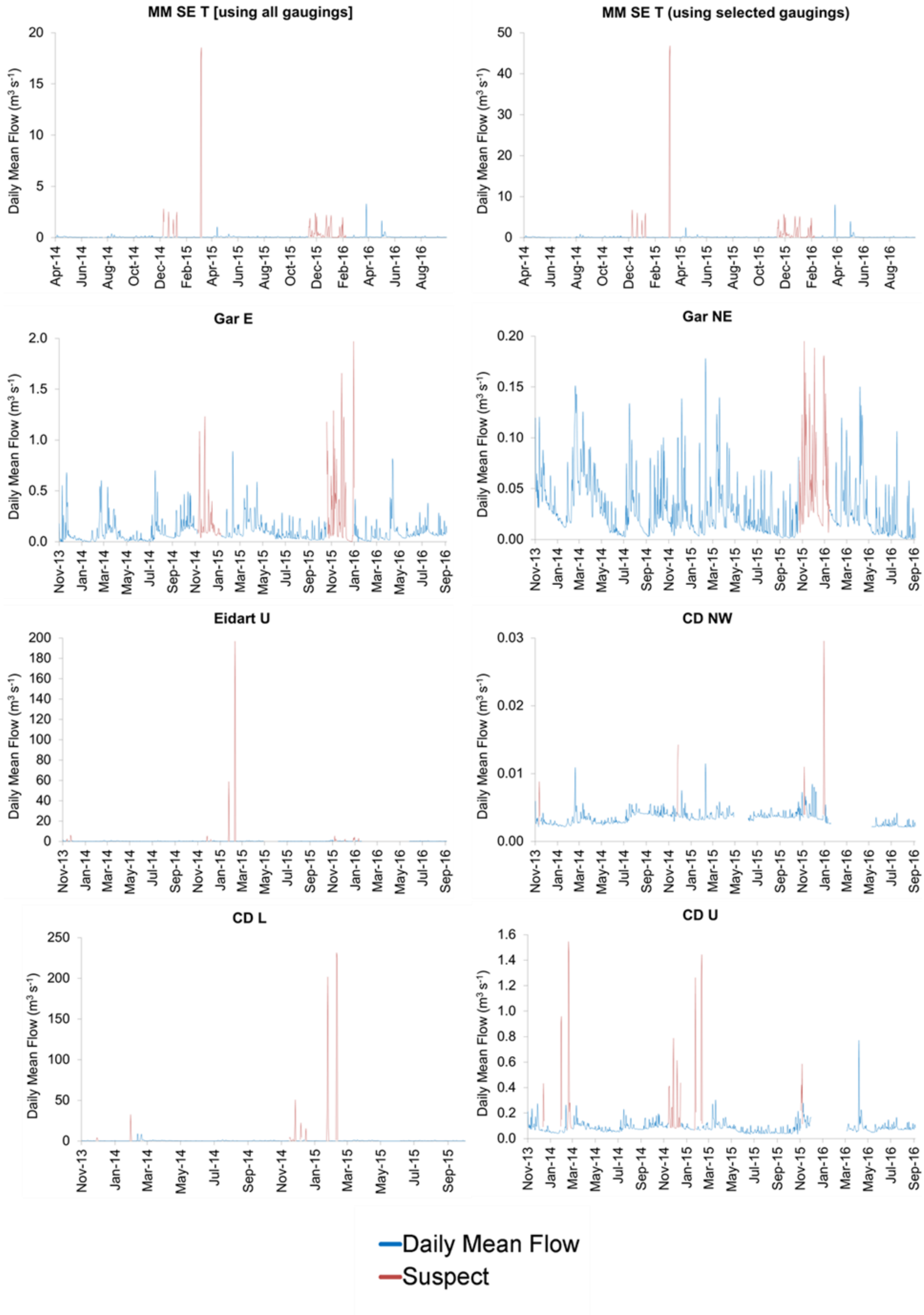


Figure 5-12: Mean gauged daily flow across the monitored streams

The daily mean flow is shown in blue and areas of suspect data where the flows are believed to be due to the weight of the snowpack on the HOBO have been highlighted in red. The flows were calculated using the selected gaugings rating curve (Equation 5 1). Suspect daily mean flow data in red has been removed from further analysis. The flow values for 2016 end on the 30th of September 2016. Given the later installation date, flow values for MM SE T start in April 2014 and due to bank collapse, CD L values end in October 2015 as predicted flow values beyond this point are deemed inaccurate. The mean gauged daily flow has been shown for flow derived from the selected gaugings option. Apart from MM SE T where the option with using all gaugings and selected gaugings have both been shown to demonstrate the differences observed.

The largest peaks in daily flow were recorded in the largest streams, the Eidart upper and Caochan Dubh lower, both on the 7th March 2015 (Figure 5-12). It was also noted that many sites were covered with ice and snow during the winter/spring months. A photograph of the Mòine Mhór south east tributary shows the frozen nature of the plateau during this time and as such these peaks have been marked as suspect (Figure 5-13). From this, it is believed that the snow caused inaccurate level recordings therefore these data points have been marked as suspect and shown in the red colour as highlighted in Figure 5-12. Removing these data points has resulted in a more realistic dataset of peak flow values.

Figure 5-13: Snow covered stream

Picture taken of MM SE T on the 11th March 2015 and shows the snow covered nature of the streams during this period. The water is noted to be flowing slowly under the snowpack.

The same data has been presented as more focused in scale to facilitate comparison of flow patterns between catchments (Figure 5-14).

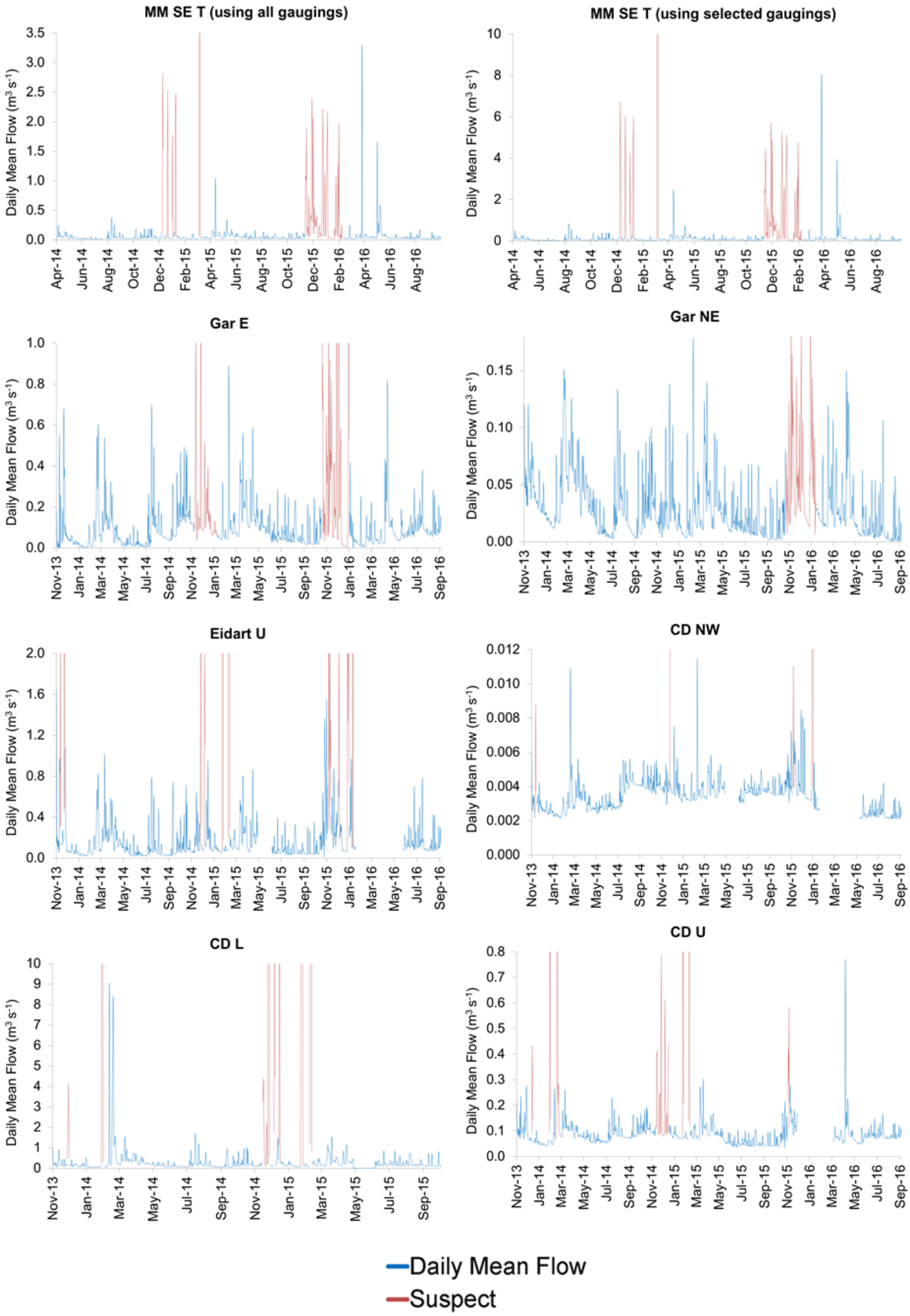


Figure 5-14: Mean gauged daily flow across the monitored stream inset

As with Figure 5-12, the daily mean flow is shown in blue, in this figure, the upper limits of the suspect data have been cut off to show the majority of the flows at the lower limits as noted by the difference in the scale bars when comparing the two figures. The flows were calculated using the selected gaugings rating curve (Equation 5 1).

The daily mean flows for Garbhlach east are notably higher in comparison to the Garbhlach north east stream attributable to the larger catchment area and represents a greater transport of water down the channel from this stream. As expected, variability is noted between the years and between the seasons however no one year greatly stands out when looking at the output as a whole in Figure 5-14.

5.3.6 Annual runoff on the Mòine Mhór

To compare between catchments, the mean daily flows were used to calculate the annual runoff previously outlined in Section 4.5.1.1. The mean flow value for the period of interest was used to calculate the annual runoff for each of the monitored catchments. This has been calculated for complete water years and for the summer months only given that for much of the winter months streams lay under metres of snow thereby impacting on the logged levels and corresponding calculated flow values. There is a slight bias in data as not all sites have a complete set of data as seen by the completeness column in Table 5-7. As previously indicated in Section 5.3.4 the annual runoff figures have been shown for the flows generated using all gaugings and with flows using excluded gaugings for comparative purposes.

Table 5-7: Annual runoff values for the monitored streams on the Mòine Mhór

Summer season covers from 1 June to 31 August. Year is based on a water year which runs from 1 October through to 30 September. Completeness follows removal of suspect data and is calculated from daily mean flow values. Completeness is also impacted by periods where logger was not recording due to logger data storage becoming full in the winter months at certain locations.

Stream	Dates based on	Completeness (%)	Annual runoff (mm)
CD L	2014/15	82	1736
	Summer 2014	100	1397
	Summer 2015	67	1514
CD L (all gaugings)	2014/15	82	1735
CD NW	2014/15	89	584
	2015/16	68	486
	Summer 2014	100	493
	Summer 2015	67	545
	Summer 2016	100	363
CD NW (all gaugings)	2014/15	89	817
	2015/16	68	717
CD U	2014/15	89	1257
	2015/16	73	1336
	Summer 2014	100	1184
	Summer 2015	100	852
	Summer 2016	100	1222
CD U (all gaugings)	2014/15	89	1469
	2015/16	73	1707
Eidart U	2014/15	86	2878
	2015/16	60	3900
	Summer 2014	100	1886
	Summer 2015	67	1590
	Summer 2016	79	3053
Eidart U (all gaugings)	2014/15	86	2493
	2015/16	60	3255
Gar E	2014/15	83	3553
	2015/16	80	2403
	Summer 2014	100	1901
	Summer 2015	100	2174
	Summer 2016	100	2538
Gar E (all gaugings)	2014/15	83	2872
	2015/16	80	2020
Gar NE	2014/15	100	4697
	2015/16	77	3775
	Summer 2014	100	4159
	Summer 2015	100	3104
	Summer 2016	100	2173
Gar NE (all gaugings)	2014/15	100	7803
	2015/16	77	6228
MM SE T	2014/15	95	2640
	2015/16	76	3594
	Summer 2014	92	2004

	Summer 2015	100	2049
	Summer 2016	100	1543
MM SE T (all gaugings)	2014/15	95	1474
	2015/16	76	1839

The Standard Average Annual Rainfall (SAAR) for the Mòine Mhór from 1691 to 1990 was 1649 mm and the 1941 to 1970 average annual rainfall was 1782 mm. In comparison, lower in the valley of the River Feshie, the SAAR from 1961 to 1990 was 1286 mm and the 1941 to 1970 average annual rainfall was 1286 mm (NERC (CEH), 2019). Annual runoff values for the Mòine Mhór would not be expected to exceed the SAAR value of 1782 mm. In comparison to this, the values reported in Table 5-7 are higher than expected for Eidart upper, Garbhlach east, Garbhlach north east and Mòine Mhór south east tributary. The Caochan Dubh lower, Caochan Dubh north west and Caochan Dubh upper are within a more expected range and are below the 1782 mm value. The all gaugings runoff number for the Mòine Mhór south east tributary slightly removes the weighting off the high gauging (Figure 5-11) however it was decided to leave it in on the selected gaugings option as it presented one of the few high gaugings recorded in the dataset. This results in the selected gaugings producing a higher runoff value (2014/15, 2640 mm) when compared to the all gaugings option (2014/15, 1474 mm). This has also occurred for the Caochan Dubh lower, Eidart upper and Garbhlach east sites. As stated previously (Section 4.5.1.1), small catchment areas can substantially affect the reliability of the runoff value which may help to explain these overestimations. Indeed, as the catchment area increases the annual runoff value is expected to decrease. The delineation of the topographical catchment areas (Figure 4-4) can differ from the true extent of the contributing area (underground flows and inputs of water) which may account for the higher values for the Garbhlach streams (National River Flow Archive, 2018). However, the presentation of these values is still useful to give an expected range of runoff values typical for the Mòine Mhór streams in relation to the wider Feshie catchment (Section 5.2.4.1). Note also that the NRFA advise that annual runoff calculations for catchments of less than 100 km^2 are prone to large errors caused by small variations in measured data (refer to Section 4.5.1.1)

5.3.7 Hydrological comparison of catchments

The catchments monitored are similar in terms of the climate experienced, geology, vegetative composition and topography (Table 3-2). These similarities allow for direct comparisons of the hydrology between them (Table 5-8). The values have been calculated from the available daily flow data (completeness summarised in Table 5-2 and Table 5-7).

Table 5-8: Comparisons of the hydrology of the study site catchments

Units of flow are reported in $m^3 s^{-1}$. Flow percentiles have been derived from the available gauged daily flow data largely covering from Nov 2013 – Sep 2016. Alongside the mean flow, the three highest daily flows with corresponding dates have also been displayed for each of the monitored streams. These statistics are based on carrying forward the selected gaugings flows, apart for the mean flow where a comparison between the selected gaugings and all gaugings has been shown.

		Stream (all values reported in $m^3 s^{-1}$)						
		CD L	CD NW	CD U	Eidart U	Gar E	Gar NE	MM SE T
Flow Percentiles	Q10	0.553	0.004	0.127	0.365	0.211	0.066	0.189
	Q50	0.149	0.003	0.076	0.090	0.061	0.019	0.047
	Q70	0.110	0.003	0.066	0.062	0.037	0.012	0.035
	Q95	0.057	0.002	0.042	0.028	0.007	0.003	0.024
Mean flow		0.281	0.003	0.086	0.158	0.095	0.029	0.103
Mean flow (all gaugings)		0.272	0.005	0.103	0.134	0.082	0.048	0.056
Three highest daily flows in chronological order		09/03/14 9.059 15/03/14 5.405 16/03/14 8.336	16/03/14 0.011 07/03/15 0.011 24/12/15 0.008	14/04/15 0.302 02/05/16 0.769 03/05/16 0.309	27/11/13 1.645 21/11/15 1.329 26/11/15 1.553	07/03/15 0.872 08/05/16 0.813 09/05/16 0.771	16/03/14 0.150 07/03/15 0.175 02/05/16 0.150	14/04/15 2.474 27/03/16 8.038 02/05/16 3.965

The flow percentage of 10 % exceedance (Q10) is considered high flow and ranges from 0.553 to 0.004 $m^3 s^{-1}$ in comparison to 15.69 $m^3 s^{-1}$ of the River Feshie (Section 5.2.5). The median (Q50) is within the range of normal flows and ranges from the lowest value in the Caochan Dubh north west to the highest value in the Caochan Dubh lower. The low flows are all reported as close to zero in the smaller streams, the Caochan Dubh north west, Garbhlach north east and Garbhlach east corresponding with the smallest catchment areas (Table 4-1). Again, as indicated in Figure 5-11, the comparison between the flows created using selected gaugings and all gaugings has been shown for the mean flow across the study period. It is acknowledged that the flow statistics are calculated on a small dataset in comparison to the minimum of 10 years recommended for reliability of predicting future conditions (Searcy, 1969). The three highest flows for each of the respective streams have been displayed and all occur within the winter to spring months.

In summary, water levels, temperature, flow and annual runoff for the monitored streams for the Mòine Mhór have been characterised above. The flow values are less than the Feshie and appear realistic for the catchment sizes however, the mean annual runoff appears overestimated in the majority of the catchments and cautions against calculations based on such small catchment areas (Table 5-7). The dates of the highest daily flow vary between the monitored streams but seem to be linked with snowmelt periods (Table 5-8). A dominant determinant of water chemistry is stream temperature which can regulate dissolution and precipitation reactions (Langan *et al.*, 2001). The chemical properties of the water quality varies with the water flow regime, however there is a close correlation between the two (Nilsson and Renöfält, 2008). Flow and temperature alongside the catchment inputs can impact on the water chemistry, an area which is now explored in relation to the study site and associated data collected on the Mòine Mhór.

5.4 IHACRES rainfall-runoff modelled flow

Following the lower confidence acknowledged in the study flow datasets (Section 5.3.4) and to provide a comparison dataset, flows were modelled for the Mòine Mhór south east tributary using the flow modelling software IHACRES (Section 4.6). The output from the model run provides values for the scaled observed stream flows against the modelled stream flow for the Mòine Mhór south east tributary (Figure 5-15). The flow values were converted to a daily flow value covering from January 2014 through to December 2017 with the graph displayed in Figure 5-15 and the summary statistic results presented in Table 5-9. The calculated annual runoff values of 1861 to 2982 mm remains comparable with the results presented in Table 5-7, again appearing to overestimate flow. The highest modelled daily flows recorded on the 11th (0.911 m^3 s^{-1}) and 12th (1.203 m^3 s^{-1}) of August 2014 were a known event. These high flows also corresponded with the highest gaugings recorded for three of the other study streams that were flow gauged on a site visit on the 12th August 2014, the Garbhlach north east (0.144 m^3 s^{-1}), Garbhlach east (0.392 m^3 s^{-1}) and Caochan Dubh lower (0.837 m^3 s^{-1}).

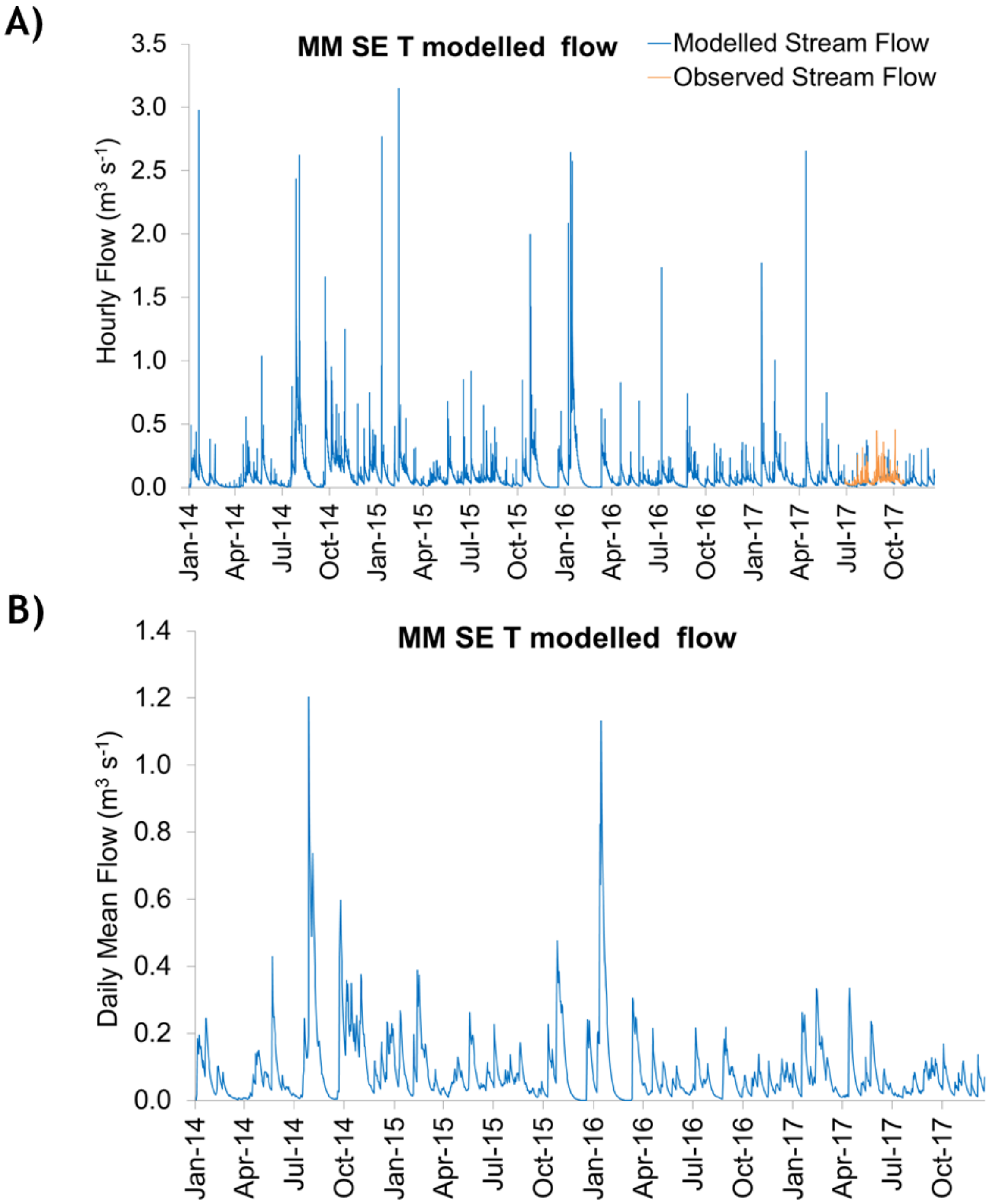


Figure 5-15: Modelled stream flow for the MM SE T

Modelled flow (blue) and observed stream flow (orange) presented as hourly flow values (a). The MM SE T modelled flow has also been displayed as daily mean flow (b).

Table 5-9: Hydrological summary for MM SE T modelled stream flow

The annual runoff values are calculated from the daily mean flow and year is based on a water year which runs from 1 October through to 30 September.

MM SE T modelled stream		
Mean flow	16/01/14 to 31/12/14	0.113 $m^3 s^{-1}$
	01/01/15 to 31/12/15	0.085 $m^3 s^{-1}$
	01/01/16 to 31/12/16	0.084 $m^3 s^{-1}$
	01/01/17 to 31/12/17	0.068 $m^3 s^{-1}$
Three highest daily flows	12/08/14	0.911 $m^3 s^{-1}$
	29/01/16	1.132 $m^3 s^{-1}$
	11/08/14	1.203 $m^3 s^{-1}$
Flow Percentiles	Q10	0.196 $m^3 s^{-1}$
	Q50	0.053 $m^3 s^{-1}$
	Q70	0.031 $m^3 s^{-1}$
	Q95	0.006 $m^3 s^{-1}$
Annual Runoff	2014/15	2982 mm
	2015/16	2618 mm
	2016/17	1861 mm

The modelled stream flows based on the lower Eidart flows scaled to the Mòine Mhór catchment helps validate the results collected from the upper streams and provide a higher level of confidence in the results collected. The modelled mean flow in 2014 of 0.113 m^3 s^{-1} in Table 5-9 is comparable with the mean measured Mòine Mhór south east tributary flow of 0.103 m^3 s^{-1} (Table 5-8). When comparing the two, there was a seasonal difference in the dates of the three highest flows, March, April and May for the Mòine Mhór south east tributary measured flows and January and August for the modelled flows. The August event was captured within the rainfall totals which fed into the calculated modelled flows with 59.4 mm of rainfall recorded on the 11th August 2014 and 16.2 mm of rainfall recorded on the 12th of August 2014. Although beyond the scope of the measured dataset, modelled flows have been displayed for 2017 and indicate that this year was drier and experienced lower flows and respective runoff values when compared to the 2014, 2015 and 2016 datasets.

An increased dataset may have helped improve the model fit and use of one continuous rainfall data series to derive the flow would have been preferential (Section 4.6). However, this again demonstrates the challenges associated with collecting an accurate and complete long-term dataset from such a remote environment without any technical difficulties. There was added difficulty in modelling flows during winter where the rain gauge may not have collected and recorded rain however there is still flow in the streams during this time. The result displays a hydrograph fit where flow that was modelled relatively well for the purpose of a comparative dataset (Figure 5-15). The expected rise and falls in flow are evident throughout the time series although the shape shows a slightly jaggy response pattern which is not as realistic, overall indicating the result is still not as trustworthy. Repeating seasonal patterns are not as evident in the modelled daily mean flow with lows and high peaks occurring in various months across the years.

5.5 Precipitation across the Mòine Mhór

Precipitation inclusive of rain, snow, sleet or other atmospheric water vapour that falls or condenses under gravity is the greatest factor controlling streamflow. Of particular interest here is the influence of precipitation on the river flow and water chemistry. The study site is located in the Cairngorms and is positioned in the north east of Scotland. Precipitation values sourced from the Met Office for the study years of 2013 to 2016 are reported in Table 5-10 showing the north, east and Scotland as a whole.

Table 5-10: Amount of precipitation (mm) and precipitation days (>1 mm) from the UK climate network of observing stations

Annual regional values are reported for the region of Scotland, Scotland north and Scotland east due to the positioning of the study site in the north east of Scotland (Met Office, 2017a).

Region	Precipitation (mm)				Days of precipitation (> 1 mm)			
Year	2013	2014	2015	2016	2013	2014	2015	2016
Scotland	1474	1757	1854	1535	180	203	207	188
Scotland N	1609	1853	1984	1649	197	214	227	204
Scotland E	1074	1366	1353	1207	153	180	178	168

In terms of years captured, the precipitation was 85-95 %, 115-125 %, 105-115 % and 95-105 % of the 1981-2010 average during 2013, 2014, 2015 and 2016 respectively (Met Office, 2017a). This indicates that the precipitation was similar to the 1981-2010 average as 100 % indicates the same amount of precipitation in the respective year of interest in comparison to the longer term average. Across the study period, the least amount of precipitation and precipitation days was recorded in 2013, although not exceptionally so, while the most precipitation occurred in 2015, apart from in Scotland east where the highest precipitation and precipitation days were recorded in 2014.

5.5.1 Precipitation summary

An annual precipitation summary over the study years is provided to set context for the reported water chemistry results in Section 5.6.

5.5.1.1 Study year 2013

Across the UK and with particular reference to the Cairngorms, the precipitation amount in October and December 2013 was greater than 200 % of the 1981-2010 average. This means that double the amount of precipitation fell in December 2013 when compared to the long term average. The total amount of precipitation that fell during December 2013 made it the wettest calendar month in Scotland on record since 1910 (Met Office, 2014a). The rest of the year was close to the average in terms of annual statistics and precipitation totals.

5.5.1.2 Study year 2014

Overall, it was wetter than average in the east of Scotland during 2014 (>135 % as seen in Figure 5-16). Winter storms in January and February 2014 brought with them damaging winds and flooding, both inland and coastal (Met Office, 2014b). Later the same year, the north east of Scotland was affected by the remnants of hurricane Bertha on the 10th of August 2014 which brought with it, strong winds, heavy rain and flooding. The automatic weather station situated at Allt a'Mharcaidh in the Cairngorms recorded a total of 214.6 mm during the month of August 2014, considerably higher than the rainfall of 85.3 mm for August 2015 (Figure 5-17).

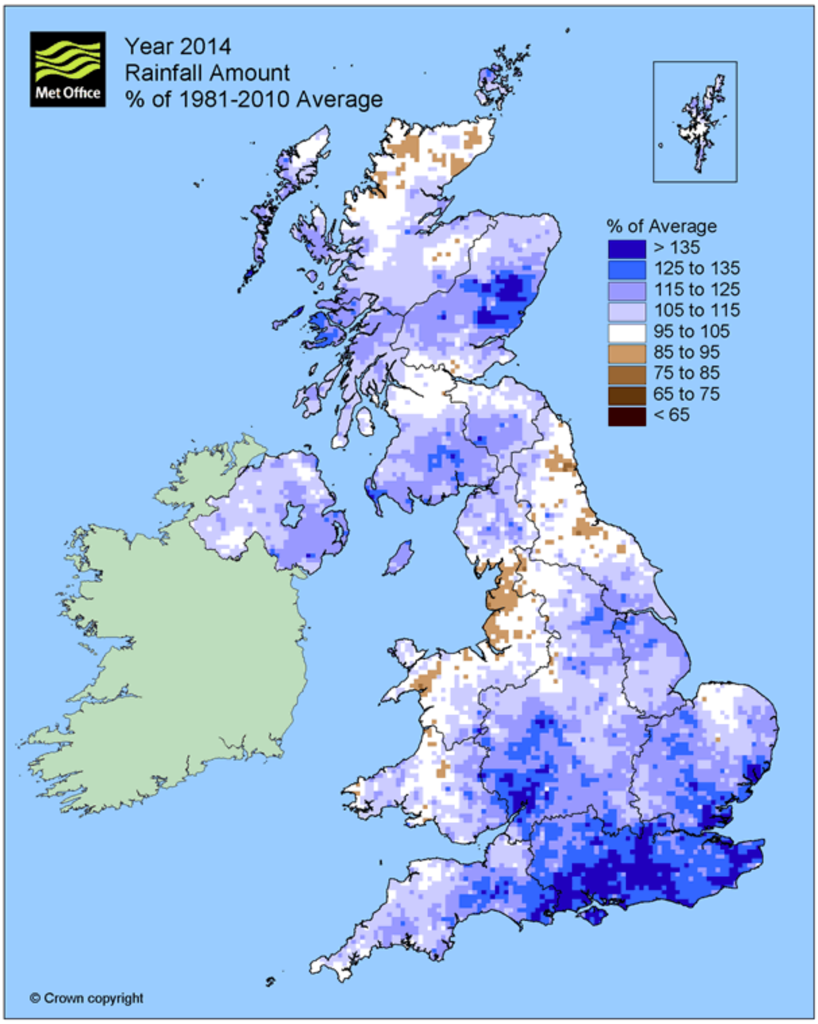


Figure 5-16: Precipitation amount for 2014 displayed as % of the 1981-2010 average

An annual period of precipitation displayed in relation to a 30 year long term average for across the UK. Note the wetter than average precipitation amount recorded in the east of Scotland during 2014 in relation to the long term average. Source: Met Office (2017a).

5.5.1.3 Study year 2015

The weather was mostly calm up until mid-November 2015. Named Atlantic storms that were first introduced in autumn 2015 included Storms Desmond, Eva and Frank and represent a more unsettled period of weather. Greater than twice the 1981 – 2010 average total precipitation amount fell during December 2015 across southern Scotland (Met Office, 2017b).

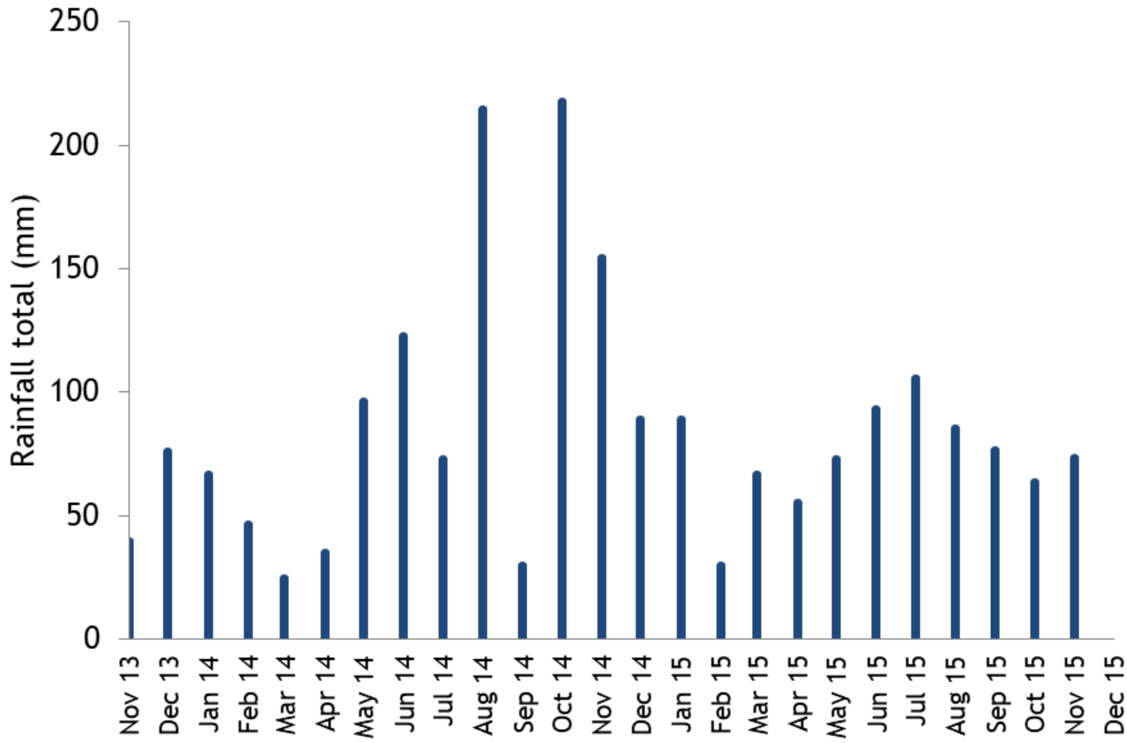


Figure 5-17: Allt a'Mharcaidh Automatic Weather Station (AWS) monthly precipitation totals

The Allt a'Mharcaidh AWS is part of the UK Environmental Change Network (ECN). The catchment area drains to the River Feshie and is situated in the north west of the Cairngorms. Monthly precipitation totals were downloaded from the ECN Data Centre covering from November 2013 to November 2015. Data for 2016 was unavailable and therefore not displayed (ECN Data Centre, 2017).

5.5.1.4 Study year 2016

In 2016, no individual regions deviated beyond 10 % of the 1981-2010 long term averages for annual precipitation totals. January and June 2016 were notably wet, whereas October and December 2016 were notably dry. Winter storms that came in late January to late March 2016 included Gertrude, Henry, Imogen, Jake and Katie which brought with them high winds reaching gusts in excess of 40 m/s. This resulted in disruption and damages inclusive of power outages, large coastal waves, blizzard conditions, road closures and localised flooding in the impacted weather warning areas across the UK (Met Office, 2017c).

5.5.2 Precipitation throughout Glen Feshie

To assess the precipitation for the study site in more detail and at a more local level than in Section 5.5.1, data from a variety of University of Dundee operated automatic weather stations (AWS) and tipping bucket rain gauges (TBR) have been utilised (location map available in Figure 4-8). None of these sites have operated continually through the study period, so some substitutions of data from sites at greater distance and lower altitude have been considered to fill the gaps. The first choice in terms of data collected was the Ridge AWS which is positioned on the western ridge of Drium nam Bo at an elevation of 900 m. The Ridge AWS sits at the same altitude as the Mòine Mhór and is located less than 2 km from the centre of the plateau, therefore the data can be regarded as comparable. The AWS was installed on the 1st of August 2015 therefore data before this period was sourced from Meur Shuas TBR which was chosen as a second choice. Meur Shuas sits at the slightly lower elevation of 692 m and is located 6 km from the centre of the plateau. Meur Shuas is still considered a high level gauge whereas Carnachiun, Chomhraig and the gliding club are classed as lower altitude gauges. If any other gaps existed these were filled in by other local monitoring points referred to as Carnachiun (AWS3), Chomhraig (TBR), gliding club (AWS) and storage gauge 7 (SG7). The 15-minute total precipitation amounts for each of the monitored sites across the available data range are shown in Figure 5-18.

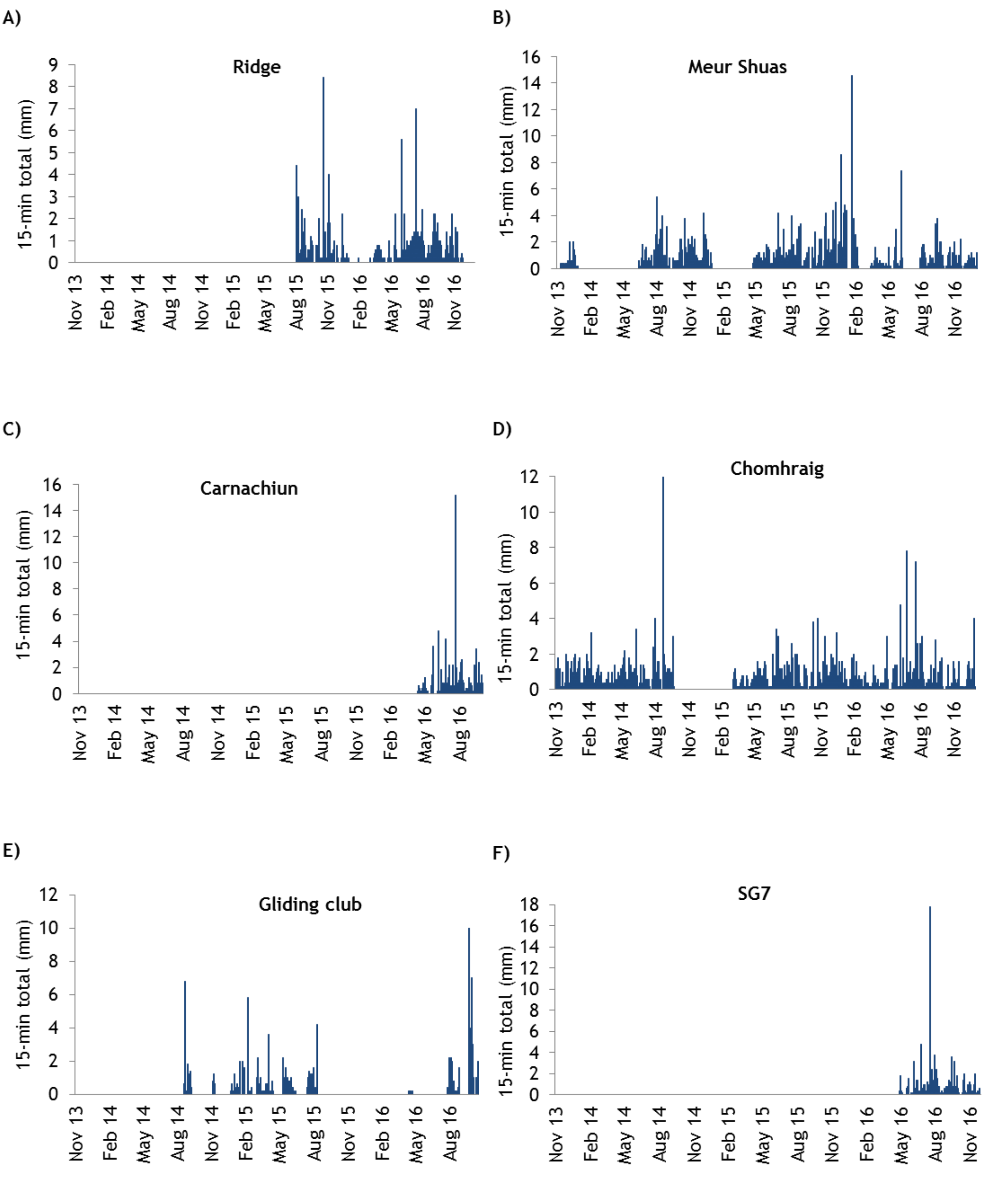


Figure 5-18: Precipitation data for Glenfeshie available during the study period

15-minute precipitation totals for the Ridge (A), Meur Shuas (B), Carnachiun (C), Chomhraig (D), Gliding Club (E) and SG7 (F).

The accumulated precipitation was then calculated from the inferred 15-minute plots across the time series of interest. With available data from 2013, 2014, 2015 and 2016, the accumulation plots for the first and second choice (Ridge and Meur Shuas) are displayed graphically in Figure 5-19.

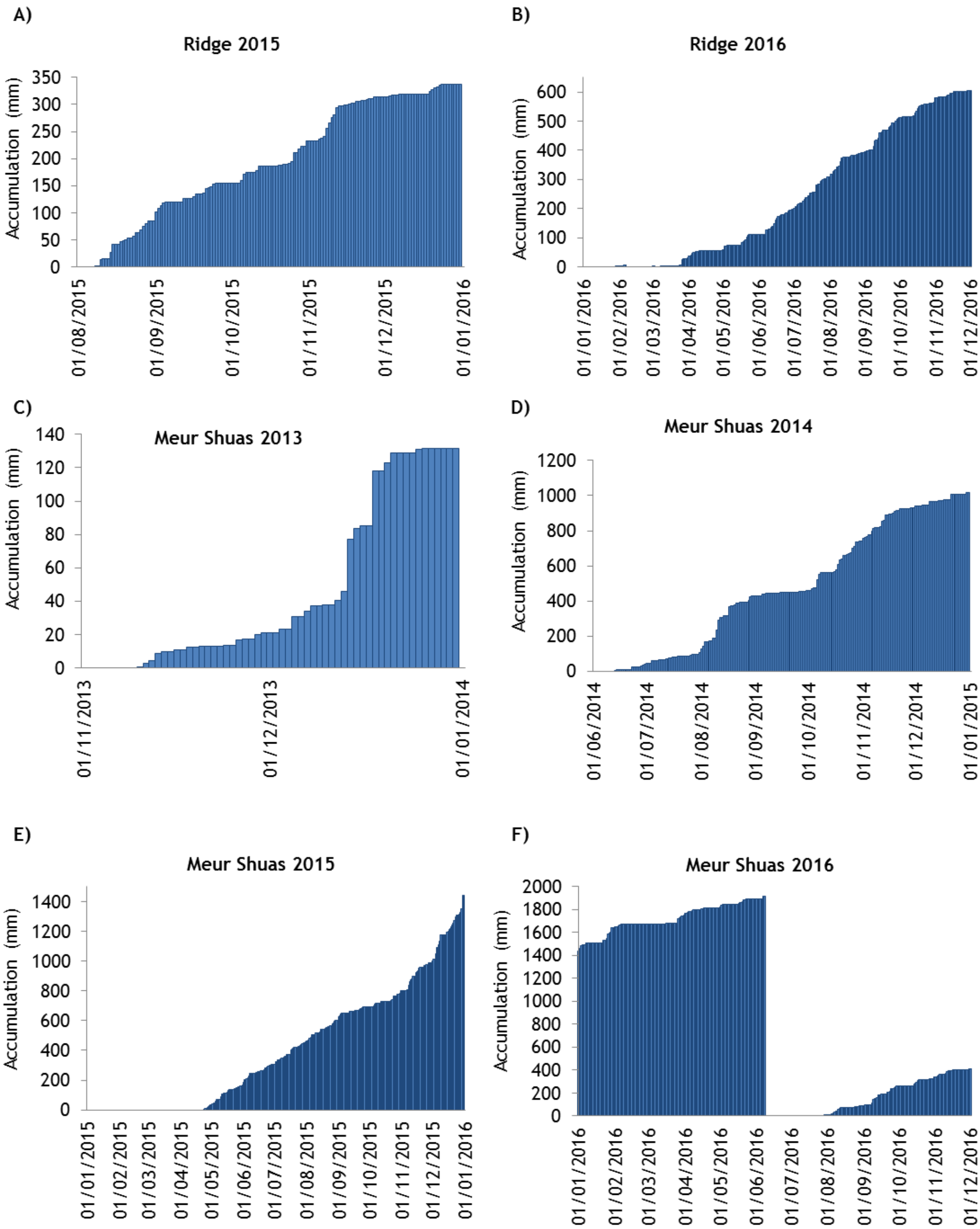


Figure 5-19: Combined accumulation precipitation data for Glenfeshie

Accumulation precipitation totals for the Ridge in 2015 (A) and 2016 (B) as well as Meur Shuas in 2013 (C), 2014 (D), 2015 (E) and 2016 (F). Meur Shuas 2015 data excluded from 01/01/2015 to 24/04/2015 as no accumulation recorded, TBR under snow cover for this period. The gap in Meur Shuas 2016 was caused by blockage problems from the 8th of June up until the 29th of July. Note that not all graphs start on 1st January due to some data gaps.

Accumulation gives an idea as to the total depth of precipitation that fell over the catchment area over a specified time. As stated previously, precipitation also includes snowfall and the weather stations are not able to distinguish between snow and rain. However, snowfall periods can be inferred based on season and temperature. Tipping bucket rain gauges record when melting snow passes through a gauge. Heating can be applied to the buckets to avoid error arising from water freezing in the buckets, subject to an available power source. Such power was supplied from solar and wind generation through most of winter 2015/16 at the Ridge AWS.

Precipitation values for the study years of 2013 to 2016 are reported in Table 5-11 showing the results from the Ridge, Meur Shuas, Carnachiun, Chomhraig, MM SG and SG7. A number of the years are incomplete due to limited resources in terms of time and the difficulty in accessing some of the site locations for these stations throughout the winter months (snow covered, freezing temperatures *etc.*). Where gaps exist, these have been detailed in the notes section at the bottom of Table 5-11 with each note relating to a corresponding station precipitation value. In terms of a complete dataset, a precipitation total of 1439 mm was recorded for 2015 at Meur Shuas. In relation to the Met Office data this is higher than Scotland east but lower than Scotland north and Scotland overall. For 2016, a precipitation total of 925 mm was recorded at Chomhraig. This value is lower than the Met Office data, 282 mm less than Scotland east overall where the lower value may be attributable to the water being locked up in a snowpack.

Table 5-11: Amount of precipitation (mm) recorded from the Glenfeshie hydro-meteorological monitoring network.

Annual values are reported in order of applicability for the study site across the years 2013 to 2016.

Station	Precipitation (mm)			
Year	2013	2014	2015	2016
Ridge	N/A	N/A	338 [†]	616 [‡]
Meur Shuas	132 [+]	1019 *	1439	959 ^
Carnachiun	N/A	N/A	N/A	445 [>]
Chomhraig	308 <	838 ∞	996 [§]	925
MM SG	N/A	510 [$]	663 -	597 [%]
SG7	N/A	N/A	N/A	284 “

† - Based on 146 days data. AWS installed on 7 Aug 2015.
‡ - Based on 284 days data. Missing 51 days, issue’s through winter (Jan, Feb, and March 2016) responsible for the gaps in the dataset.
+ - Based on 53 days data. From 8 Nov – 31 Dec 2013.
* - Based on 245 days data. Missing 119 days, large gap from 13 Feb to 13 June 2014.
^ - Based on 315 days data. Missing 50 days, blockage problem from 8 Jun – 29 Jul 2016.
> - Based on 172 days data. From 13 Apr – 2 Oct 2016.
< - Based on 60 days data. From 1 Nov – 31 Dec 2013.
∞ – Based on 267 days data. From 1 Jan – 25 Sep 2014.
§ - Based on 300 days data. From 6 Mar – 31 Dec 2015.
$ - Based on 85 days data. From 11th Sep – 5th Dec 2014.
- - Based on 266 days data. From 7th Jan – 30th Sep 2015.
% - Based on 150 days data. From 3rd Jun – 31st Oct 2016.
“ - Based on 213 days. From 29th Apr – 28th Nov 2016.

In relation to the monitored streams, the Garbhlach east site sits within the Mullach Chlach á Bhlàir catchment area which represents the highest point within the study area and represented the most exposed location within the plateau. The Mòine Mhór storage gauge sat within the Mòine Mhór south east tributary catchment area. This gauge provides an estimate of the total precipitation on the plateau but unfortunately it did not have a large enough capacity (held 77 mm and would often overflow) or emptied regular enough to be fully reliable. This appears to have resulted in an underestimation of the precipitation totals possibly due to the loss of precipitation as a result of the smaller gauge size.

To provide a more complete and comparative dataset, the Cairngorm ECN automatic weather station (AWS) rainfall values have also been presented. The daily rainfall totals across the study period of interest are displayed in Figure 5-20. Comparable with the site specific summary table, an annual summary table for the Cairngorm ECN AWS is also provided in Table 5-12.

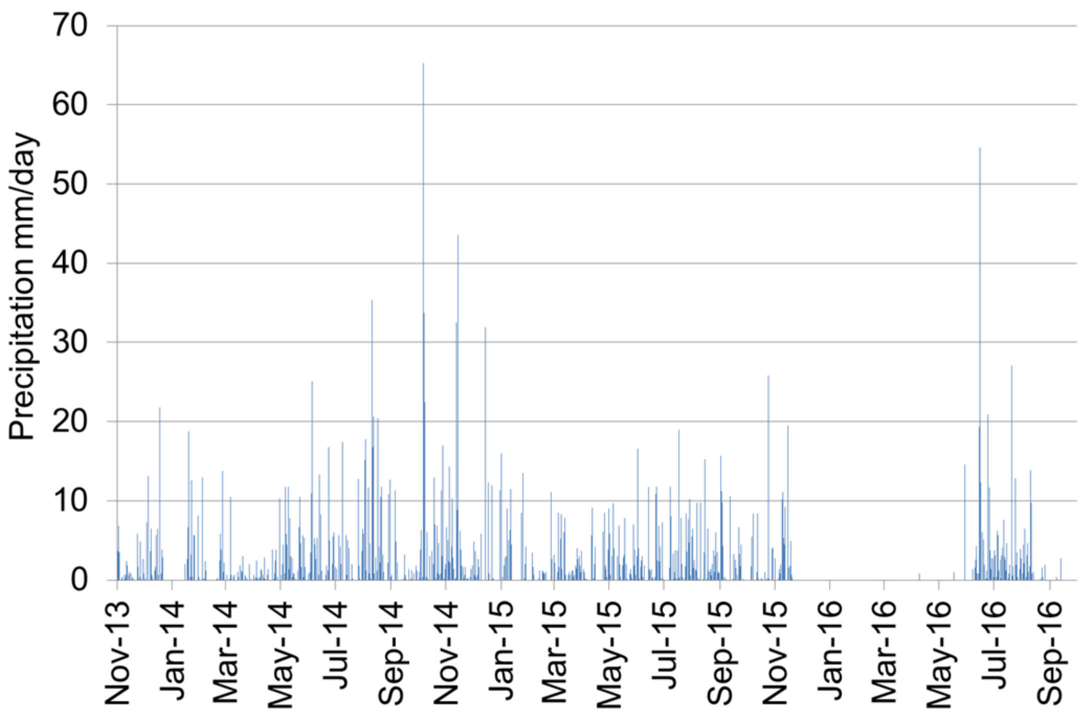


Figure 5-20: Precipitation data for the Cairngorm ECN AWS available during the study period

Table 5-12: Amount of precipitation (mm) recorded from the Cairngorm ECN AWS

Station	Precipitation (mm)			
Year	2013	2014	2015	2016
Cairngorms ECN AWS	116 †	1170 ‡	811 +	338 *

† - Based on 60 days data. Study period of interest from 1 Nov – Dec 2013.
‡ - Based on 352 days data. Missing 1 Jan to 14 Jan 2014.
+ - Based on 320 days data. Missing 30 Jun to 5 Jul and 21 Nov to 31 Dec 2015.
* - Based on 260 days data. From Jan to Sep 2016. Missing 1 Jan to 14 Jan 2016.

Although largely complete, there are still periods of missing data with the Cairngorms ECN dataset, mostly observed during the winter months. The most complete years of 2014 and 2015 recorded 1170 mm and 811 mm of precipitation. Given the lack of compete data from the Glenfeshie hydro-meteorological monitoring network it is hard to draw direct comparisons with the data. The Meur Shuas gauge recorded higher rainfall in 2014 when compared to 2015, which is the opposite from the Cairngorm ECN values. However, this may be explained by the missing values from the Meur Shuas gauge in 2015 resulting in an underestimation of precipitation for this year.

Given the greater completeness of the dataset, the relationship of the Cairngorms ECN data and the study stream response times were explored. When looking at the data in more detail for individual events, the relationship between flow and rainfall is apparent with an example of the relationship shown in Figure 5-21.

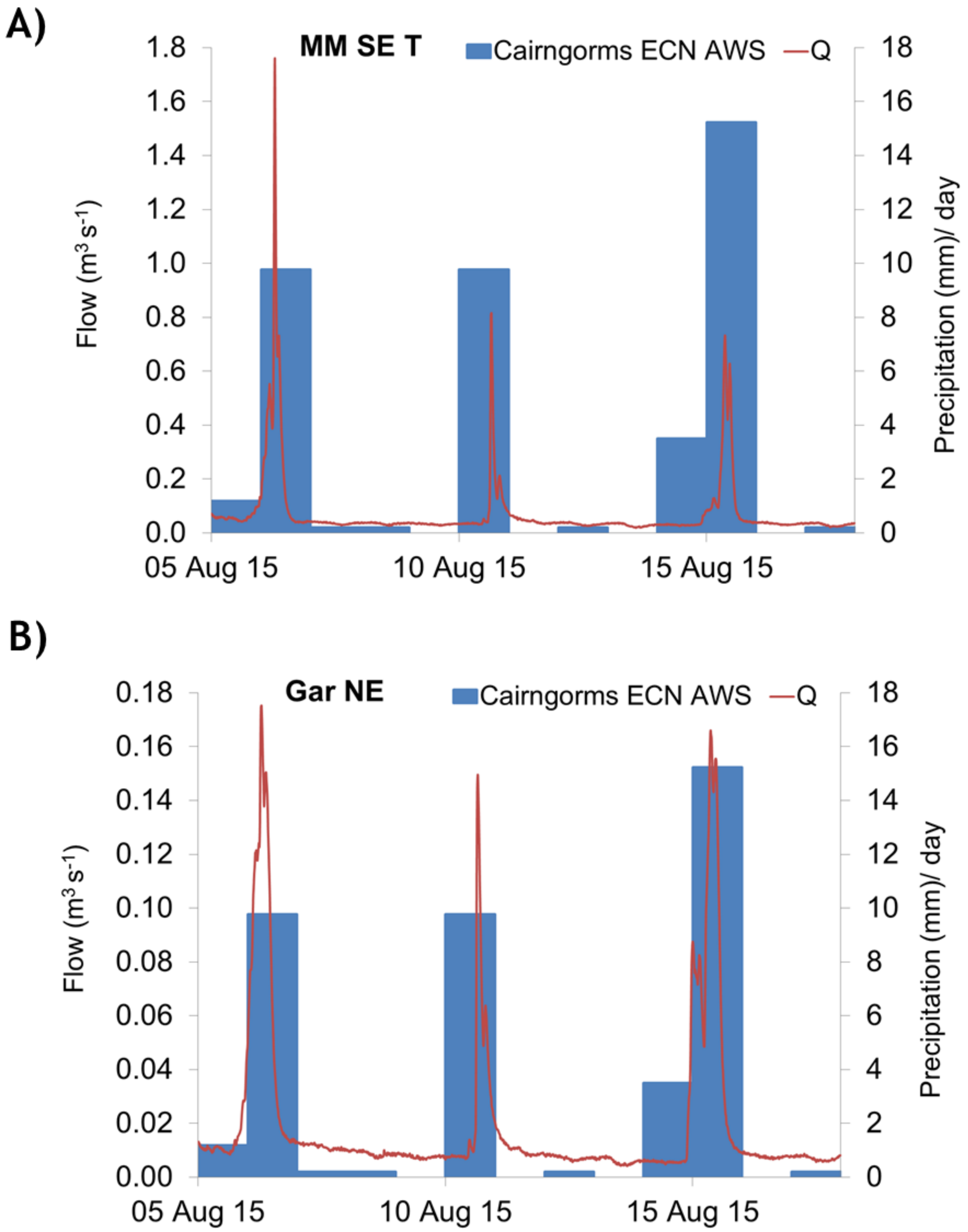


Figure 5-21: Relationship between precipitation and flow

The daily precipitation data has been displayed for the Cairngorms ECN AWS and corresponding flow values at the MM SE T (A) and Gar NE (B) are also shown.

Between the monitored streams displayed in Figure 5-21, the peaks in flow happened at the same time in response to the precipitation recorded. The flow peaked at 6:30 am at the Garbhlach north east (0.175 m^3 s^{-1}) and at 6:45 am at the Mòine Mhór south east tributary (1.761 m^3 s^{-1}) on the 6th August 2015 in response to a daily total of 9.77 mm of rainfall. On the 10th August 2015, in response to 9.77 mm of rainfall, the flow peaked at 3:45 pm at both sites with 0.150 m^3 s^{-1} maximum flow recorded at the Garbhlach north east and 0.816 m^3 s^{-1} recorded at the Mòine Mhór south east tributary. The flow peaked at 8:45 am at the Garbhlach north east (0.166 m^3 s^{-1}) and at 09:00 am at the Mòine Mhór south east tributary (0.732 m^3 s^{-1}) on the 15th August 2015 in response to a daily rainfall total of 15.23 mm.

The difficulty in recording complete datasets during the winter months was again highlighted with reference to the presentation of the precipitation data sources collected on site and from utilising other datasets. It is evident that flow has a close relationship with precipitation as demonstrated previously in the modelled flows for the event in August 2014 (Section 5.4), with the Met Office summary statistics (Section 5.5.1.2) and with reference to the Cairngorm ECN dataset and the flows presented in Figure 5-21. The monitored streams are very responsive to these events and of note to the next section is how the water chemistry responds to the peaks in flow observed.

5.6 Chemical properties of the water sampled from the Mòine Mhór

The collection of water samples can aid the understanding of natural processes in the environment alongside the impact of humans on the ecosystem. Water quality monitoring can also be used to help with restoration projects. Data could be collected during baseline, throughout works and post remedial works or to ensure that environmental standards are being met. The parameters chosen for laboratory analysis (Section 4.14) allow quantification of the overall ecological condition of the water draining the study site.

5.6.1 Laboratory results from analysed water samples

5.6.1.1 Samples collected

To complement the level, flow and precipitation data collected, as highlighted in Section 4.3, grab water samples were collected from all eight streams. Across the project timeline, 17-42 water samples were collected from each location on the Mòine Mhór (Table 4-9). The smallest number of water samples collected was in the Eidart upper as it was the furthest stream monitored from the study site access. The Eidart would also remain snow covered and thus inaccessible for a longer period of time when compared with the other monitored streams. The highest number of samples was collected from the Mòine Mhór south east tributary as this was where the spectro::lyser was also located, which required regular downloads.

For each stream, on each study site visit, three samples (where possible) were collected and analysed. The mean value calculated was then used in the data analysis. The data presented has used all laboratory results collected apart from dissolved oxygen where erroneous values that exceeded the maximum upper known limits for dissolved oxygen in water were removed from further analysis (Section 4.7). There was a small variability in the laboratory results between samples for absorbance, pH, dissolved oxygen and conductivity. Graphs for the Caochan Dubh lower, a representative stream, showing the values and standard deviation between replicate samples, on each sampled date, is displayed in Figure 5-22. In the other monitored streams, the standard deviation was generally smallest for absorbance, all standard deviation were below 0.029 at 400 nm, and all below 0.190 at 254 nm. The standard deviation for pH was also small across the sampled streams with all deviating by less than 0.5 indicating that the streams are relatively similar in these tested parameters. Overall, the larger standard deviations were observed for dissolved oxygen and conductivity, however, as seen in Figure 5-22, taking a mean of the three replicates gives increased confidence in the values obtained from the calibrated laboratory handheld instruments (Table 4-3). Larger standard deviations seem to be observed when higher readings were recorded although all values collected were considered representative of the stream water at the time of sampling and analysis.

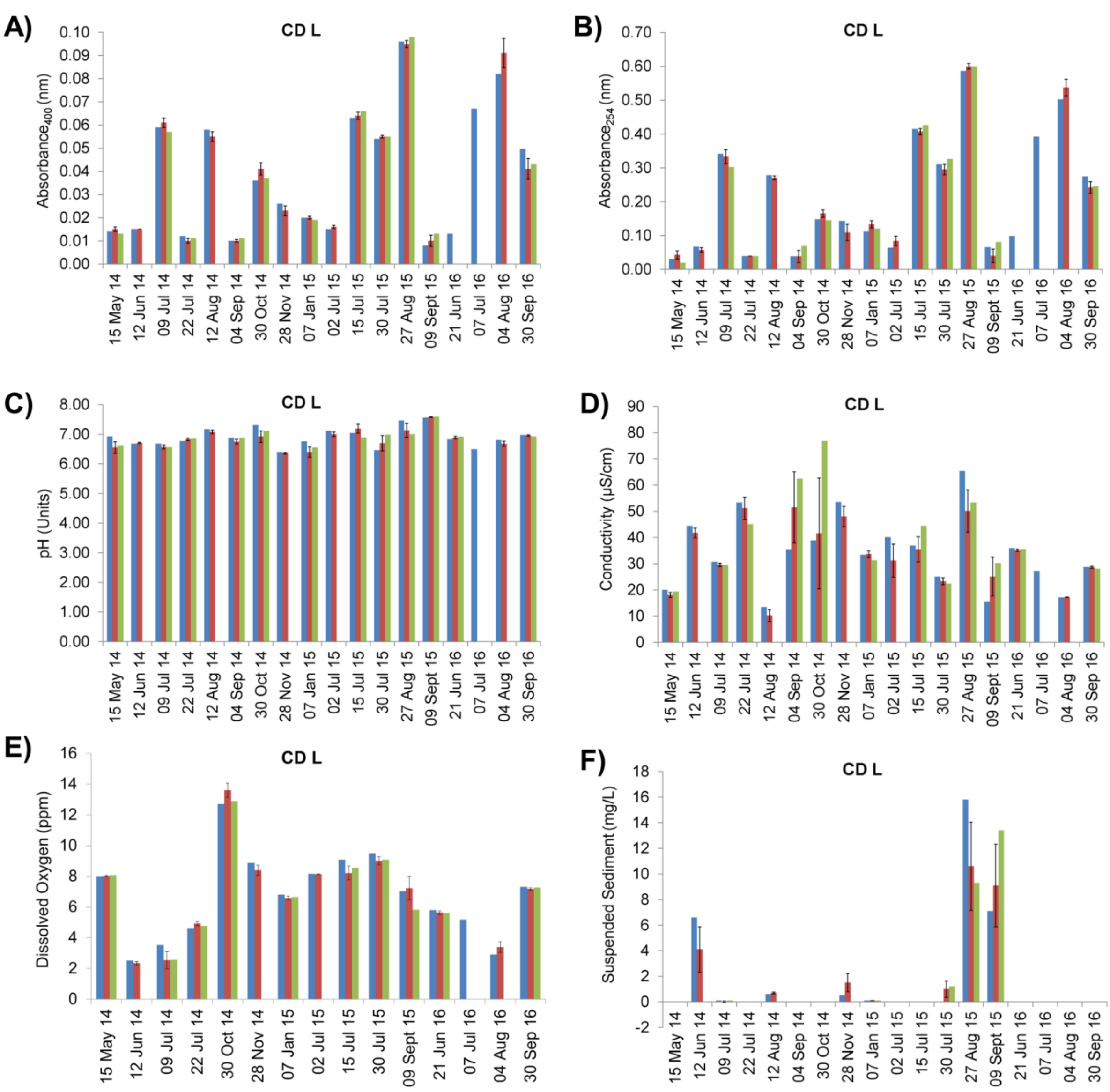
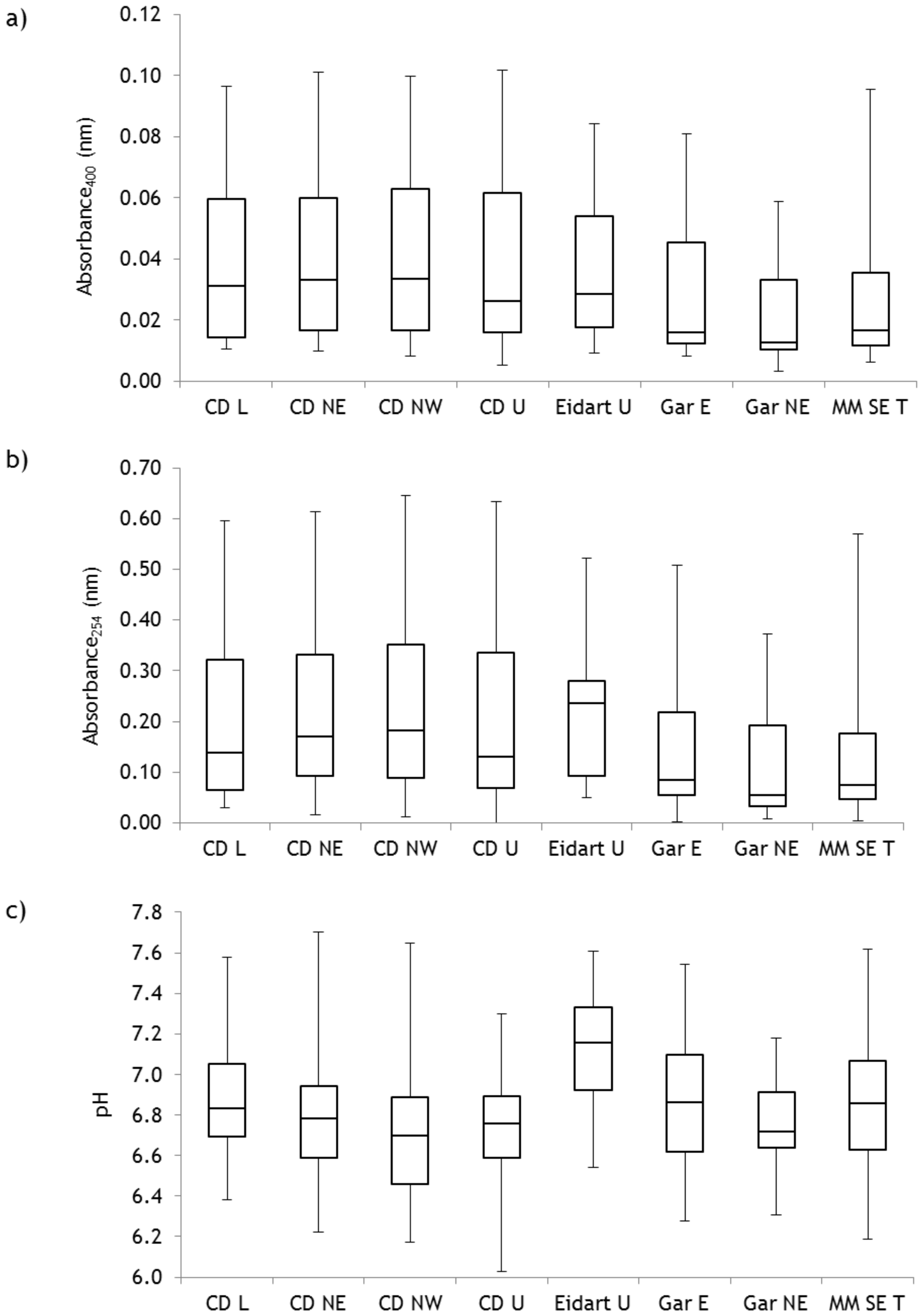


Figure 5-22: Replicate samples for CD L

Graphs showing the variability between each set of replicate samples for absorbance at 400 nm (A) and 254 nm (B), pH (C), dissolved oxygen (D), conductivity (E) and suspended sediment (F). Standard deviation is shown by a plus and minus error bar. For presenting results, a mean of the replicates where available was taken. Note that three water samples collected were not collected on every occasion. On days when walking only one/two samples were collected to ease rucksack load.

The results presented herein from each monitored stream are dervied from the mean of the multiple samples collected at each sampling location. Upon returning from the field (Figure 4-6) and analysis in the laboratory (Section 4.14), the sample results were graphed. Initally, box and whisker plots (Figure 5-23) were created to give an indication of the variation and spread in values recorded across the sampling period.


a)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Absorbance400 (nm)
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T
b)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Absorbance254 (nm)
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T
c)
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
pH
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T

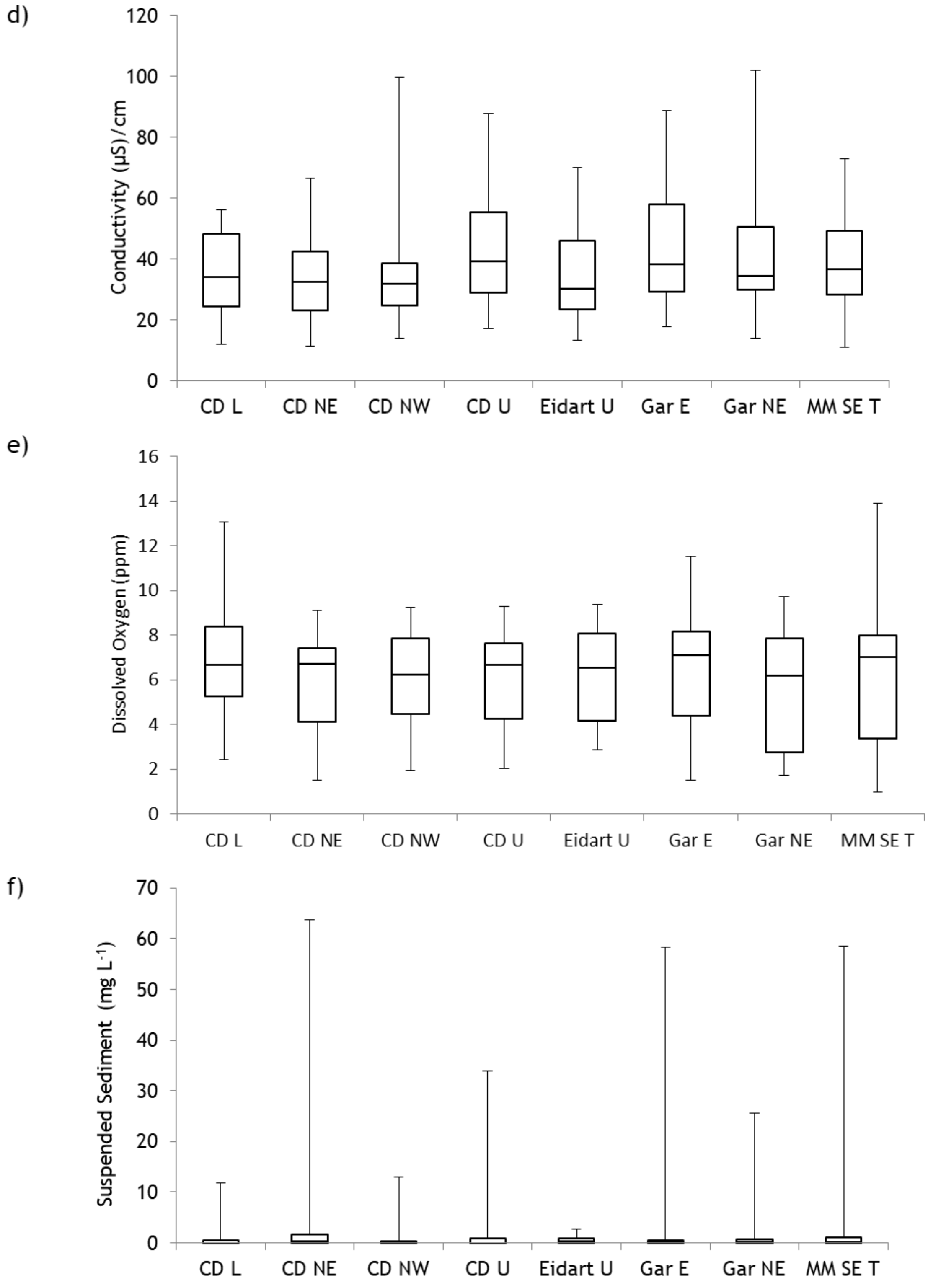


Figure 5-23: Box and whisker plots for various parameters tested for monitored streams

The minimum, first quartile, median, third quartile, and maximum of the dataset are shown for for absorbance measured at 400 nm (a) and 254 nm (b), pH (c), conductivity (d), dissolved oxygen (e) and suspended sediment (f). n = 17 – 42 as stated in Table 4-9.

To summarise the observations, selected summary statistics are presented for the monitored streams in Table 5-13. Using a spectrophotometer to measure the colour of the water, the mean absorbance at 400 nm and 254 nm across all sites respectively was 0.034 ± 0.002 nm and 0.183 ± 0.012 nm highlighting that the water was generally very clear. Using a pH probe, the water sampling indicated that collectively the monitored streams sat within normal ranges and had a slightly neutral to acidic mean pH of 6.84 ± 0.02. However, as seen in Figure 5-23, the Eidart upper had a more basic pH in contrast with other upland blanket bogs in Scotland where they can have strongly acidic pH with values as low as 4 (Urban *et al.*, 1989). The pH of the Mòine Mhór streams can be summarised as circumneutral (Scott *et al.*, 1998) with small scale variability observed. A characteristic feature of peatlands is a lower acidic pH. The more alkaline pH of the Eidart may reflect the contribution of water from the weathered mineral surface. In comparison, in a peatland where there were multiple soil pipes present, the pH was more coloured and acidic as a result of the contact of the water with the acidic upper organic soil horizons of the peat (Labadz *et al.*, 2010).

Conductivity is a useful baseline parameter to measure as it allows for any potential deterioration in the water quality to be detected, such as pollution incidents or changes to land use. The mean conductivity for all sites was 38.84 ± 1.28 µS/cm; most streams are expected to have a fairly constant range of conductivity under normal circumstances, which has been shown in the monitored streams. For all forms of aquatic life, the concentration of dissolved oxygen (DO) found in fresh waters is of importance. The overall mean DO content taken of all the Mòine Mhór sites sits within ideal healthy concentrations of 6.16 ± 0.21 ppm. This is compared to a high standard of dissolved oxygen in the Freshwater Fish Directive of 6 mg/l indicating the moderately oxygen rich standard of the monitored streams (UK Technical Advisory Group, 2008).

Suspended sediment in the water represents a removal of carbon from the peatland. High concentrations can indicate poor water quality and have impacts on siltation levels within the stream as the material settles out on the river-beds. Many suspended sediment values fell below the limit of detection with a mean value of 3.37 ± 0.75 mg/L but during storm events concentrations could increase by up to 10-fold, with values above 35 mg/L captured during high flow events. On 11 out of 31 sampling trips (35 %), no suspended sediment was extracted from the filtering process. This may have been skewed by the access constraints during wetter weather conditions, however samples were successfully captured across a range of weather conditions. Similar findings were also observed in an upland blanket peatland site in Central Scotland where access was not constrained (Bryder, 2012). On average, on 5 out of the 14 sampling trips (36 %) to the five wind farm impacted streams and the three control streams – the suspended sediment concentration in the grab samples was below the limit of detection with no significant difference detected in suspended sediment between the disturbed and control catchments. The means were also noted as similar to the Mòine Mhór study streams with a mean of 3.08 ± 0.73 mg/L in the impacted streams and 3.73 ± 0.97 mg/L in the control streams (Bryder, 2012).

The values reported show the standard error is never more than 0.3 % (pH) to 22 % (suspended sediment) of the mean which suggests that the sample mean is an accurate representation of the population mean and reproducible. Individual mean values for each of the sampled streams are summarised in Table 5-13 where small scale variances between the monitored streams can be observed.

It is also relevant to look at the spread of values in the sample, for example calculating the standard deviation (Table 5-13). The mean pH across all streams does not show much variability (6.84 ± 0.33 Units). The other measured variables highlight that there was a variety of water chemistry conditions captured across the sampling period (highlighted by the higher mean standard deviation value for other monitored parameters in Table 5-13).

Table 5-13: Summary statistics for each of the streams monitored

The mean, minimum (Min), maximum (Max), standard deviation (SD) and standard error (SE) is shown for each of the monitored streams and for each respective monitored parameter.

Parameter	Stream	Mean	Min	Max	SD	SE
Abs 400 (nm)	CD L	0.040	0.010	0.096	0.029	0.007
	CD NE	0.043	0.010	0.101	0.029	0.006
	CD NW	0.042	0.008	0.100	0.029	0.006
	CD U	0.037	0.005	0.102	0.027	0.005
	Eidart U	0.037	0.009	0.084	0.024	0.006
	Gar E	0.029	0.008	0.081	0.023	0.005
	Gar NE	0.022	0.003	0.059	0.017	0.004
	MM SE T	0.027	0.006	0.096	0.024	0.004
	Mean	0.034	N/A	N/A	0.026	0.002
Abs 254 (nm)	CD L	0.210	0.031	0.595	0.167	0.039
	CD NE	0.239	0.016	0.613	0.184	0.039
	CD NW	0.238	0.013	0.645	0.190	0.042
	CD U	0.197	0.001	0.633	0.171	0.035
	Eidart U	0.219	0.050	0.523	0.146	0.035
	Gar E	0.155	0.003	0.509	0.137	0.028
	Gar NE	0.116	0.008	0.374	0.114	0.025
	MM SE T	0.140	0.005	0.569	0.149	0.024
	Mean	0.183	N/A	N/A	0.161	0.012
pH (units)	CD L	6.86	6.38	7.58	0.29	0.070
	CD NE	6.81	6.22	7.70	0.35	0.070
	CD NW	6.75	6.17	7.65	0.40	0.090
	CD U	6.74	6.03	7.30	0.26	0.050
	Eidart U	7.11	6.54	7.61	0.29	0.070
	Gar E	6.88	6.28	7.54	0.33	0.070
	Gar NE	6.74	6.31	7.18	0.24	0.050
	MM SE T	6.88	6.19	7.62	0.34	0.050
	Mean	6.84	N/A	N/A	0.330	0.020
Conductivity (µS/cm)	CD L	35.1	11.8	56.3	13.0	3.05
	CD NE	33.4	11.5	66.6	13.5	2.81
	CD NW	35.8	14.0	99.8	19.2	4.20
	CD U	42.5	17.1	87.9	19.1	3.82
	Eidart U	36.2	13.3	69.9	17.8	4.32
	Gar E	43.6	17.7	88.8	19.7	3.93
	Gar NE	42.9	14.1	101.9	21.2	4.62
	MM SE T	38.8	11.0	72.8	16.4	2.52
	Mean	38.8	N/A	N/A	17.7	1.28
Dissolved oxygen (ppm)	CD L	6.84	2.44	13.1	2.67	0.69
	CD NE	5.92	1.50	9.13	2.28	0.52
	CD NW	5.97	1.95	9.26	2.34	0.59
	CD U	5.96	2.04	9.31	2.33	0.53
	Eidart U	6.22	2.90	9.36	2.35	0.71
	Gar E	6.40	1.50	11.5	2.87	0.64
	Gar NE	5.76	1.72	9.74	2.75	0.67
	MM SE T	6.24	0.98	13.9	2.95	0.51
	Mean	6.16	N/A	N/A	2.59	0.61
Suspended sediment (mg/L)	CD L	1.59	0	11.9	3.62	0.85
	CD NE	4.92	0	63.8	14.2	2.97
	CD NW	1.61	0	12.9	3.79	0.85
	CD U	3.24	0	33.9	8.32	1.66
	Eidart U	0.61	0	2.80	0.82	0.20
	Gar E	5.06	0	58.4	14.1	2.82
	Gar NE	2.38	0	25.5	6.66	1.45
	MM SE T	4.82	0	58.6	13.6	2.10
	Mean	3.37	N/A	N/A	10.4	0.75

The highest (maximum) and lowest (minimum) values allow comparisons between the sites to be explored (Table 5-13). The three highest values for Abs_{400} and Abs_{254} were collected on the Caochan Dubh (north west tributary, north east tributary and upper site). When comparing the sites, the values recorded were similar and highlight that during events a comparable amount of suspended sediment is mobilised from across the Caochan Dubh catchment. The lowest absorbance value measured was from the Garbhlach north east. This stream was consistently lower indicating the clearest water, possibly attributable to the completeness of the surrounding vegetative cover in comparison to the other monitored catchments. Across the monitored streams, the mean pH ranged from 6.03 to 7.7, which is within drinking water quality standards (Scottish Water, 2015). The highest conductivity values of 101.90 and 99.8 μS/cm were recorded in Garbhlach north east and Caochan Dubh north west respectively; however, the Garbhlach east had the highest mean conductivity overall. Mean DO ranged from 1-14 ppm in the Mòine Mhór south east tributary whereas the other sites were more constrained. The maximum values of the dataset are with the range of 9-14 ppm, typical of freshwater streams (Center for Innovation in Engineering and Science Education, 2018). It is acknowledged that colder water can hold more DO than warmer water with the higher readings observed to be in the autumn months (Center for Innovation in Engineering and Science Education, 2018). All sites had suspended sediment below the limit of detection on occasions. Conversely, the highest suspended sediment values were from the Caochan Dubh north east (63.8 mg/L), Mòine Mhór south east tributary (58.6 mg/L) and the Garbhlach east (58.4 mg/L). This shows that there is variation in maximum and minimum values between the sites. The significance of the differences between the streams is explored next.

According to the significance scale defined in Section 4.8, the 1-way ANOVA results showed no significant differences (p value > 0.05) in the water quality between the monitored catchments for conductivity, dissolved oxygen and suspended sediment (Table 5-14). Absorbance at wavelength 254 nm had a p value of 0.059, which sits very close to the significance threshold but is not significant. Absorbance at wavelength 400 nm had a p value of 0.035 indicating that there was a significant difference in water clarity between the monitored streams across the study period. There is a notable difference in the median and mean values between the streams to the southern end of the plateau (Garbhlach north east, Garbhlach east and Mòine Mhór south east tributary) in comparison to the slightly higher absorbance values recorded in the streams to the northern end of the plateau. As shown in Table 5-14, pH had a p value of 0.009, which indicates very significant differences in the pH values between the monitored catchments. Again, this observation is supported by the spread in the box and whisker plots shown in Figure 5-23.

Table 5-14: 1-way ANOVA results for the variation between the monitored streams for measured water quality parameters

The sum of squares (SS) and mean square (MS) measures variation within the dataset from the mean value. Degrees of freedom (df) is the number of parameters that may vary independently, here, eight streams were sampled giving seven degrees of freedom. The p value is a probability. The F critical value is the variance between groups.

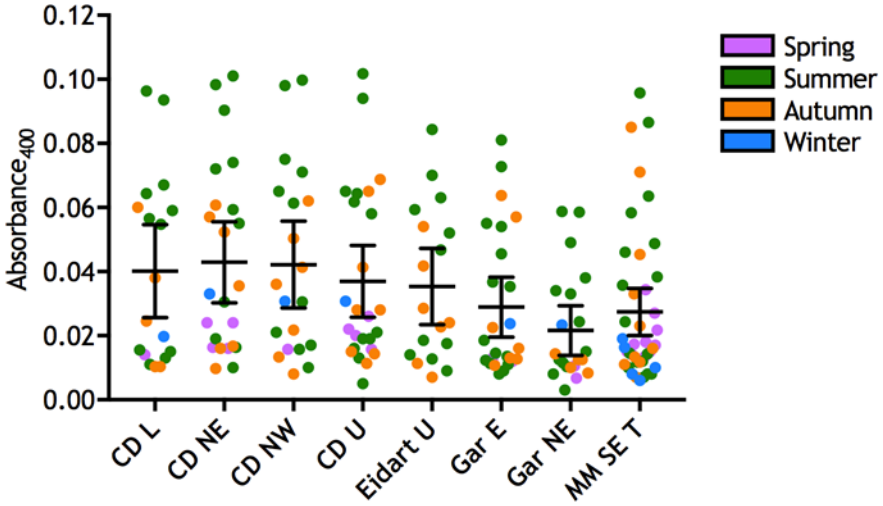
Variation between groups	*SS*	*Df*	*MS*	*F*	*P value*	*F crit*
Abs_{400}	0.01	7	0.001	2.212	0.035	2.060
Abs_{254}	0.35	7	0.050	1.987	0.059	2.062
pH	1.99	7	0.284	2.800	0.009	2.060
Con	2479.19	7	354.170	1.138	0.341	2.060
DO	13.47	7	1.924	0.277	0.962	2.074
SS	484.82	7	69.260	0.638	0.724	2.060

Where significant differences were identified from the 1-way ANOVA, a multiple comparisons test was carried out to further explore the differences between the streams (Appendix E). The significant difference in pH between the Eidart upper, Caochan Dubh upper, Caochan Dubh north west and Garbhlach north east is shown in Appendix E. Although not highlighted as significant, the p values recorded do display small differences when comparing the streams with a particular reference to absorbance.

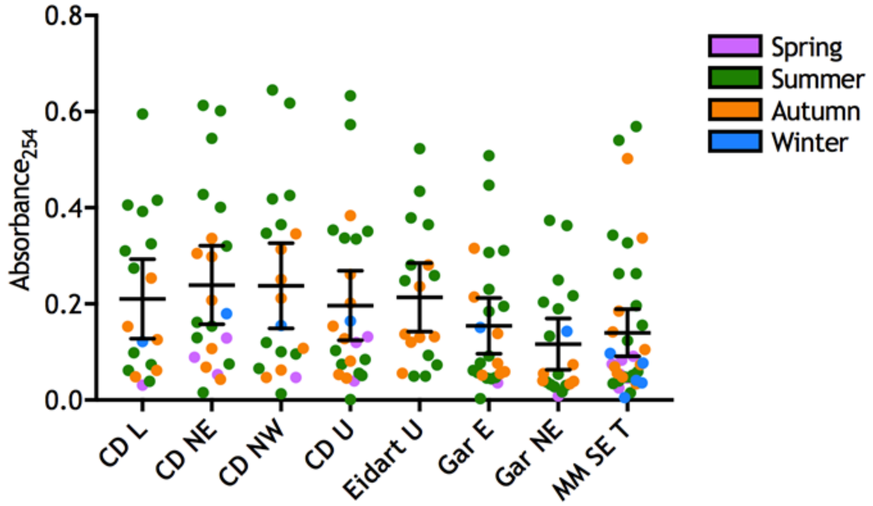
The comparison of the similarities and differences of the water quality monitoring between the eight monitored streams showed interesting similarities and differences that merited further exploration with reference to other environmental variables.

5.6.2 Seasonal water chemistry

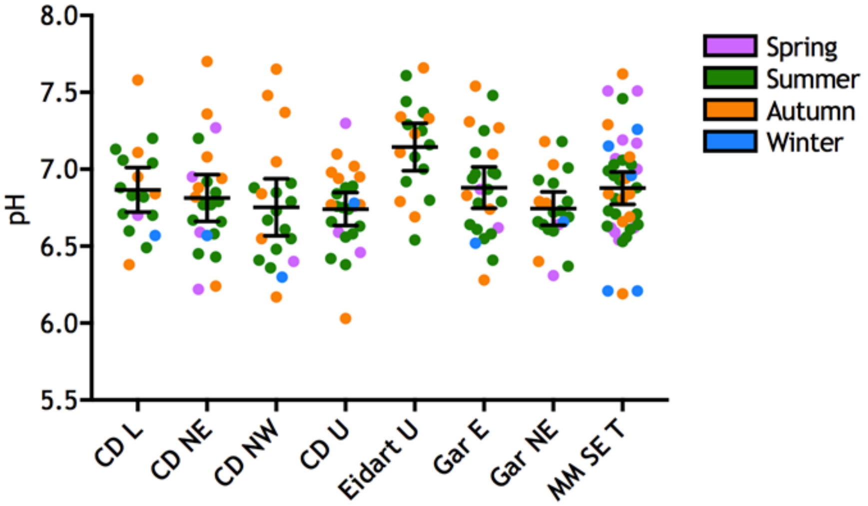
The time and flow conditions of the stream can impact on the water chemistry. A column scatterplot was created to show the seasonal variability in samples collected between sites across the study period (Figure 5-24).



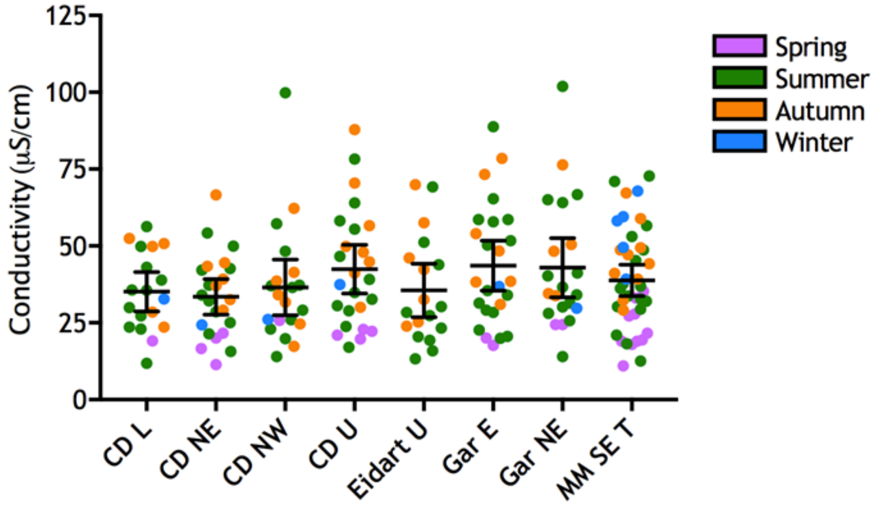
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Absorbance$_{400}$
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T
Spring
Summer
Autumn
Winter

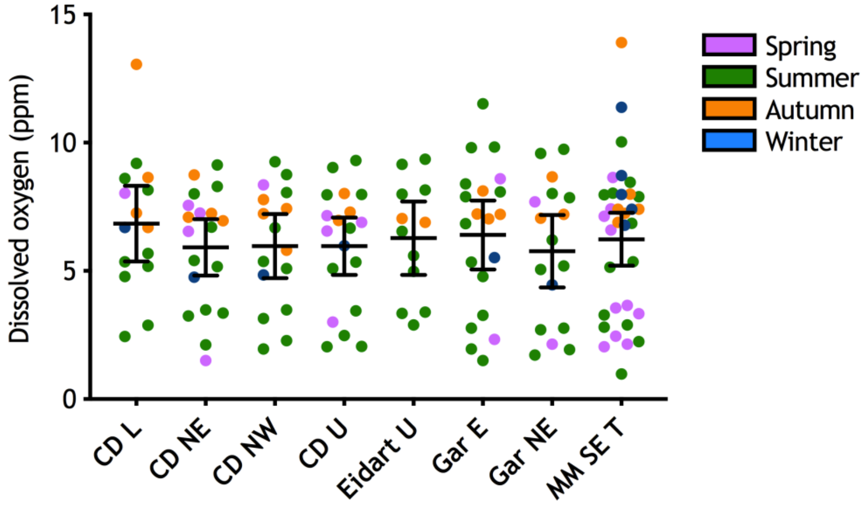


0.8
0.6
0.4
0.2
0.0
Absorbance$_{254}$
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T
Spring
Summer
Autumn
Winter



8.0
7.5
7.0
6.5
6.0
5.5
pH
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T
Spring
Summer
Autumn
Winter


Conductivity (µS/cm)
125
100
75
50
25
0
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T
Spring
Summer
Autumn
Winter


Dissolved oxygen (ppm)
15
10
5
0
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T
Spring
Summer
Autumn
Winter

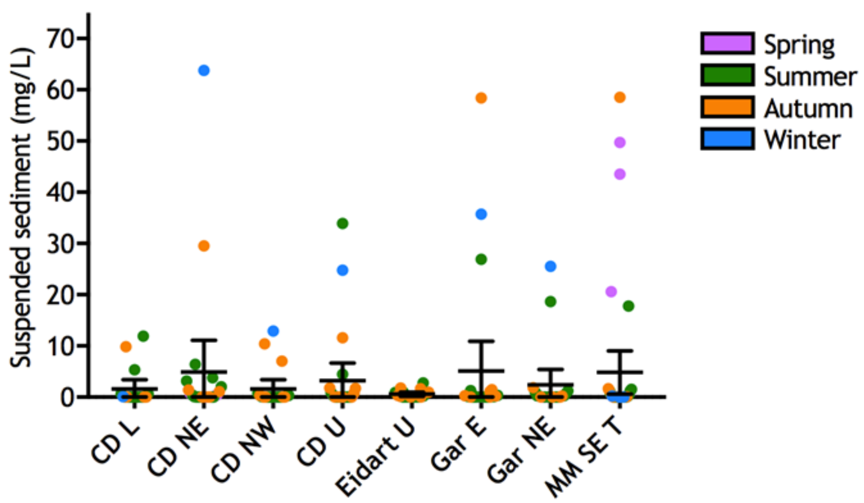

Suspended sediment (mg/L)
70
60
50
40
30
20
10
0
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T
Spring
Summer
Autumn
Winter

Figure 5-24: Column scatterplot of seasonal laboratory results for the monitored streams

The graphs for absorbance at 400 nm, absorbance at 254 nm, pH, conductivity, dissolved oxygen and suspended sediment show the mean with a 95 % confidence interval. The seasons were split up into spring (April – May), summer (June – August), autumn (September – November) and winter (December – March).

The sampling range for Figure 5-24 covers from the 15th April 2014 until the 30th September 2016. The sampling strategy consisted of regular study site visits to coincide with the download of other instruments. These would occur on days where generally there was a slightly lower flow in order to successfully access the study site. This may have caused some sampling bias although a conscious effort was made to collect samples during high flow events. Samples were categorised to cover the spring, summer, autumn and winter seasons of 2014, 2015 and 2016. In terms of a spread of data across the seasons, winter is under-represented in terms of samples collected due to the streams being snow covered and the study site largely inaccessible during those months. However, the samples that were collected are valuable in terms of the information they provide regarding the seasonal water quality on the Mòine Mhór.

With reference to the results shown in Figure 5-24, the highest absorbance values (at 400 and 254 nm) were seen in all streams in the summer months while spring had the lowest values. During the spring months the water would often remain locked up within the snowpack. As the temperature increases, the melt would happen in the summer months, which is likely the major factor for the increased absorbance values during this season. Most of the analysed samples for pH sat within the mildly acidic range of 6.58 to a neutral 7.25 with seasonal peaks experienced in the summer/autumn months and lows recorded during the winter months reflective of the seasonal hydrological differences. This was also observed in a comparable hydrogeological stream in the Cairngorms, the Allt Coire Chaoil, which was monitored monthly across a 12-year period. The pH ranged from 5.63 to 7.27 with the most acidic waters observed during the snowmelt period, covering winter and early spring (Soulsby *et al.*, 2001).

During spring, the conductivity was noticeably lower across the sites attributable to the lower flows. While in the winter season, the conductivity was around the mean value apart from at the Mòine Mhór south east tributary where it was overall slightly higher indicating greater bedrock and mineral soil erosion input. Peaks in the data were observed at all sites during the summer/autumn months, which can be attributable to increased water temperatures. Higher temperatures increase biological activity and decomposition hence increasing productivity in the streams (Dawson *et al.*, 2008). The link to water flow means that heavy rainfall or freshwater snowmelt can also cause a dilution effect reducing the conductivity in the respective seasons (Buffam *et al.*, 2007; Fondriest Environmental Inc, 2016). Overall, the higher conductivity streams (Garbhlach east, Garbhlach north east and Caochan Dubh upper) indicate greater groundwater input whereas the other streams may be summarised as more precipitation dominated. Across the monitored parameters, most of the maximum peaks appear to have been captured within the summer and autumn months. However, the analysis also shows that water quality variations occur across all four seasons contributing to the observed water quality recorded from the study streams.

5.6.3 Water chemistry and daily flow data

The water chemistry in relation to flow of the Mòine Mhór south east tributary is shown in Figure 5-25. The flow has been displayed as gauged daily flow which is the mean river flow in a calendar day (Section 5.3.5). There is no obvious relationship between water chemistry and flow. The Mòine Mhór south east tributary site was selected as an example. Graphs for all monitored streams are available in Appendix F. When flow is high this does not necessarily correlate with high water chemistry values such as for absorbance or suspended sediment. The complicated relationship between chemistry and flow in the Cairngorm headwater streams has been acknowledged from a previous study by Soulbsy and colleagues in 2001. Water chemistry was studied from four streams in the Cairngorms from 1985-1997 and indicated patterns on inter-annual variations in pH and alkalinity, with more randomly varied responses in chloride, TOC and zinc (Soulsby *et al.*, 2001).

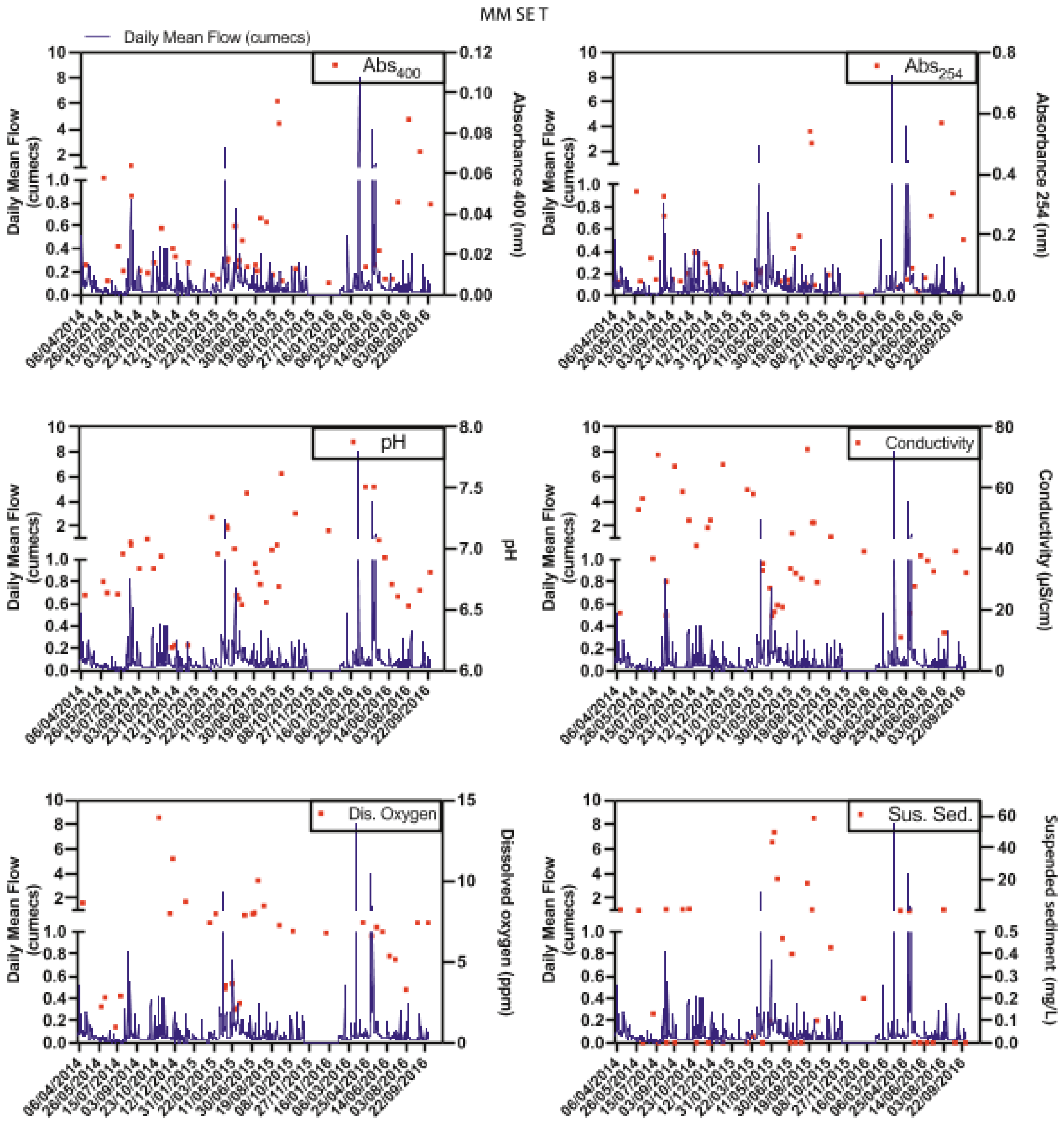


Figure 5-25: Water chemistry and daily flow values for MM SE T

Graphs show point readings [red markers] for absorbance at 400nm, absorbance at 254 nm, pH, conductivity, dissolved oxygen and suspended sediment. Daily flow [blue line] has been derived for a calendar day. A scatterplot with a secondary axis was created to show the water chemistry parameters analysed in relation to flow; graphs for all other monitored streams are available in Appendix F.

Figure 5-25 and Appendix F look at the water chemistry results collected at an overview level to see if trends are apparent. The results in relation to individual events and inclusive of rainfall, as presented in Section 5.8 may provide more details in relation to typical responses expected in the relationship between flow and water chemistry.

5.6.4 Mòine Mhór streams summary

Patterns of seasonal and inter-annual variability were investigated in the water quality parameters measured in the samples from the Mòine Mhór streams. Some significant differences in the chemistry of each stream were observed with particular reference to pH and absorbance (Appendix E). Reflective of the seasonal hydrological and temperature differences, overall maximum absorbance values were observed during the summer months, higher pH in the autumn months and minimum values for DO and conductivity were recorded during the winter months. This indicated that the influences of snow melt and winter weather conditions were evident when looking at the seasonal response of the stream. It appeared that all seasons contributed to the observed water quality with generally maximums in the water quality parameters occurring in the spring and summer months.

Overall, a good spread in the measured water quality parameters was evident, indicating that the streams were visited and sampled under a range of conditions. The clarity of the water was also evident from the absorbance values recorded which is interesting given the current condition of the site with areas of bare peat evident. Although the blanket bog habitat is generally quite acidic, the pH sat within a neutral range at the monitored streams, this was found to be generally consistent with values reported from other studies (Section 5.6.2).

5.7 Spectro::lyser data

In addition to the water samples from the previous section, water chemistry was explored on a continuous basis at one location on the Mòine Mhór by using an *in-situ* instrument known as a spectro::lyser. The spectro::lyser uses ultraviolet-visible (UV-VIS) spectroscopy to characterise the *in-situ* stream water for parameters outlined in Section 4.11.2. It was placed on a tributary of the main stream draining the Mòine Mhór from June 2014 to September 2016 (Section 4.11.3).

5.7.1 Continuous data

The spectro::lyser allows for continuous water quality monitoring. The disadvantage is that it can only be positioned within one stream, however the location chosen was located centrally within the study site (Section 4.11.1). The spectro::lyser was primarily logging at 15-minute intervals throughout the project duration. Of the intended duration from deployment on the 2nd June 2014 until data collection stopped on the 1st October 2016, based upon a continuous 15-minute logging interval, 86 % of the data was successfully logged. The loss of data is partly explained by the need to occasionally reduce the logging interval from 15-minute intervals to 30-minute and on occasions to a 1-hour logging interval during the winter months. This was carried out in order to conserve battery power and increase data storage capacity when the study site was less frequently visited.

The spectro::lyser dataset was very large. Over the duration of deployment over 90,000 individual rows of data regarding the water quality of the Mòine Mhór were generated. From this, some the data was cleaned to remove any spurious or artificially high values. The artificially high values were caused by a blockage or build-up of material on the optical lens. Figure 5-26 shows a photo and a small graph of the accompanying data for periods where despite correct orientation, the measuring path became blocked or dirty affecting the output of the data quality.

Once these had been identified and removed, this left over 48,000 rows of useable data making use of 58 % of the data collected. Although it is acknowledged that this has reduced the amount of presentable data, the data remaining provides water quality data at a higher temporal resolution.

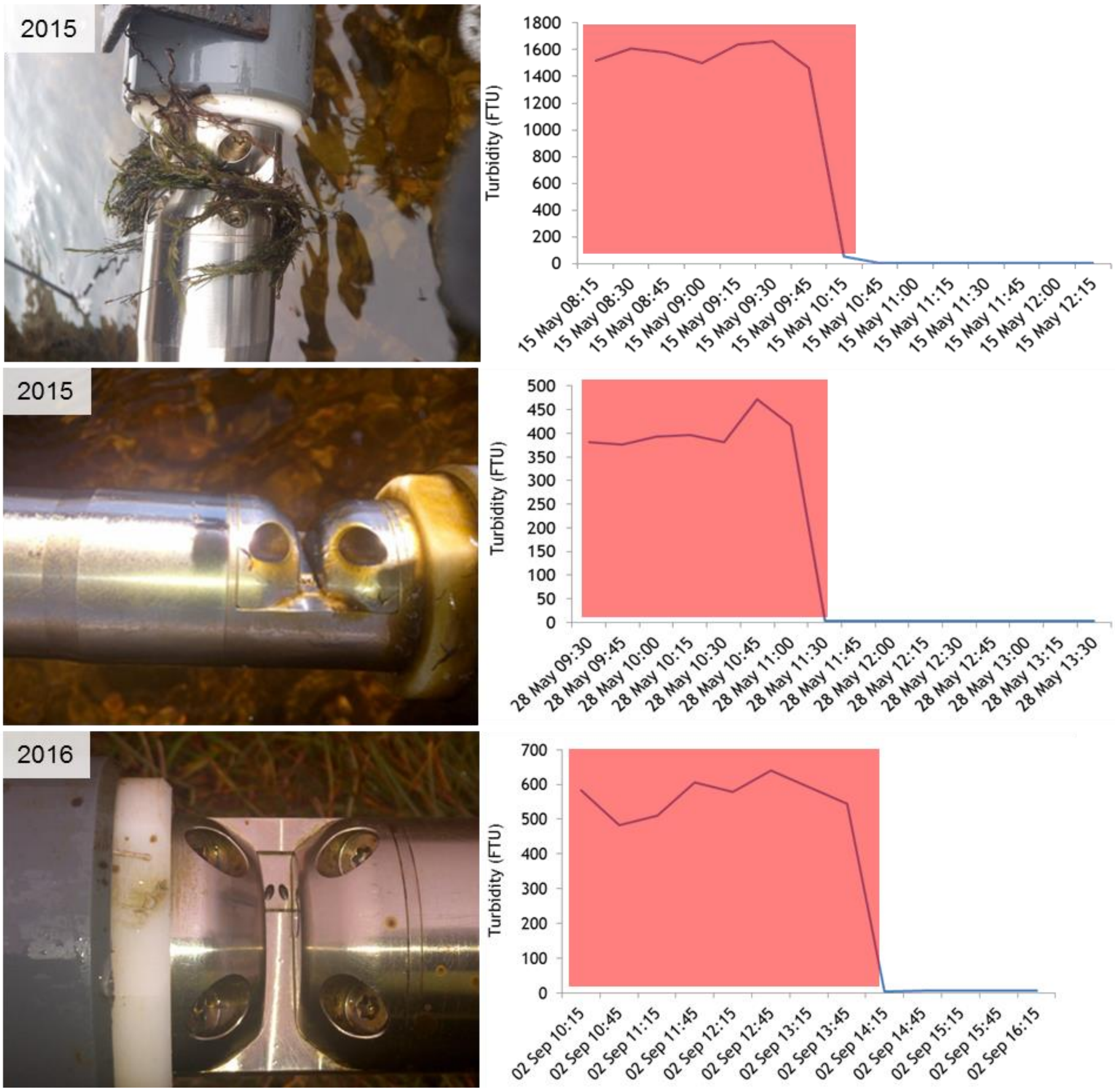


Figure 5-26: Photo of spectro::lyser before cleaning and the turbidity graph for that period

The red box on the graph indicates raw turbidity data before cleaning; this was removed from the final dataset. In addition to a build-up of material on the probe during the summer months, other gaps exist in the data due to a number of issues relating to battery power, a storm washing the instrument downstream and biological material covering the optical measuring window making some of the results unusable.

Issues in relation to biological material covering the optical measuring sensor were expected and cleaning of the optical window was carried out on study site visits. Spectro::lyser cleaning took place on a regular basis although the build-up of material on the probe during the summer months would have required almost daily cleaning to maximise the amount of useable data. Data could have been inferred for periods when the optical window was blocked although this was deemed unnecessary due to the volume of data collected across a three year time period. The cleaned dataset covers a reasonable length of time, a range of flow conditions and a variety of seasons as shown in Table 5-15 and

Figure 5-27. Given the high maxima values, it is recognised that the data may have been cleaned further however these values have been kept in on the basis that there may have been maximum concentrations that were not due to the cleanliness of the sensor. The spectro::lyser output the data for nitrate as nitrogen (NO_3-N) which has been converted to nitrate by multiplying the results by 4.43.

Table 5-15: Summary table for 2014, 2015 and 2016 spectro::lyser data

Summary statistics are calculated from the daily means, omitting suspect data and are shown for the recorded parameters of turbidity, total organic carbon (TOC), dissolved organic carbon (DOC), colour true, colour apparent and nitrate. Formazin Turbidity Units (FTU) is the most widely used measurement for turbidity. The measurement of light allows the concentration of suspended particles in the water to be determined. The colour of water is described in Hazen units (HU). True colour (ColorTr) is the colour of the sample after suspended material has been removed and apparent colour (ColorApp) contains both suspended and dissolved material. The entire absorption spectrum is used by the spectro::lyser to monitor these organic substances.

2014	Turbid.[FTU]	TOC[mg/l]	DOC[mg/l]	ColorTru[HU]	ColorApp[HU]	NO_3[mg/l]
Mean	47.0	14.7	5.81	20.1	221	0.42
Median	5.72	9.02	3.93	15.7	71.6	0.31
Standard Deviation	133	20.0	3.83	10.4	497	0.38
Skewness	4.98	4.31	1.22	0.98	4.70	4.39
Minimum	0.24	3.36	1.38	5.20	20.9	0.001
Maximum	951	135	19.2	51.9	3485	3.18

2015	Turbid.[FTU]	TOC[mg/l]	DOC[mg/l]	ColorTru[HU]	ColorApp[HU]	NO_3[mg/l]
Mean	41.8	11.5	4.86	16.6	190	0.35
Median	4.62	6.48	3.25	12.7	54.8	0.32
Standard Deviation	126	15.9	4.47	12.6	455	0.16
Skewness	5.37	4.76	2.45	3.14	5.32	3.49
Minimum	2.22	2.42	0.42	2.11	25.4	0.001
Maximum	1158	142	30.0	100	4171	1.64

2016	Turbid.[FTU]	TOC[mg/l]	DOC[mg/l]	ColorTru[HU]	ColorApp[HU]	NO_3[mg/l]
Mean	68.4	16.7	5.16	16.2	298	0.33
Median	4.78	7.42	3.97	13.0	56.9	0.33
Standard Deviation	187	25.7	4.07	10.1	694	0.08
Skewness	3.10	2.70	1.51	1.34	3.01	-0.06
Minimum	1.99	2.65	0.13	0.91	27.7	0.02
Maximum	934	122	20.1	49.5	3405	0.76

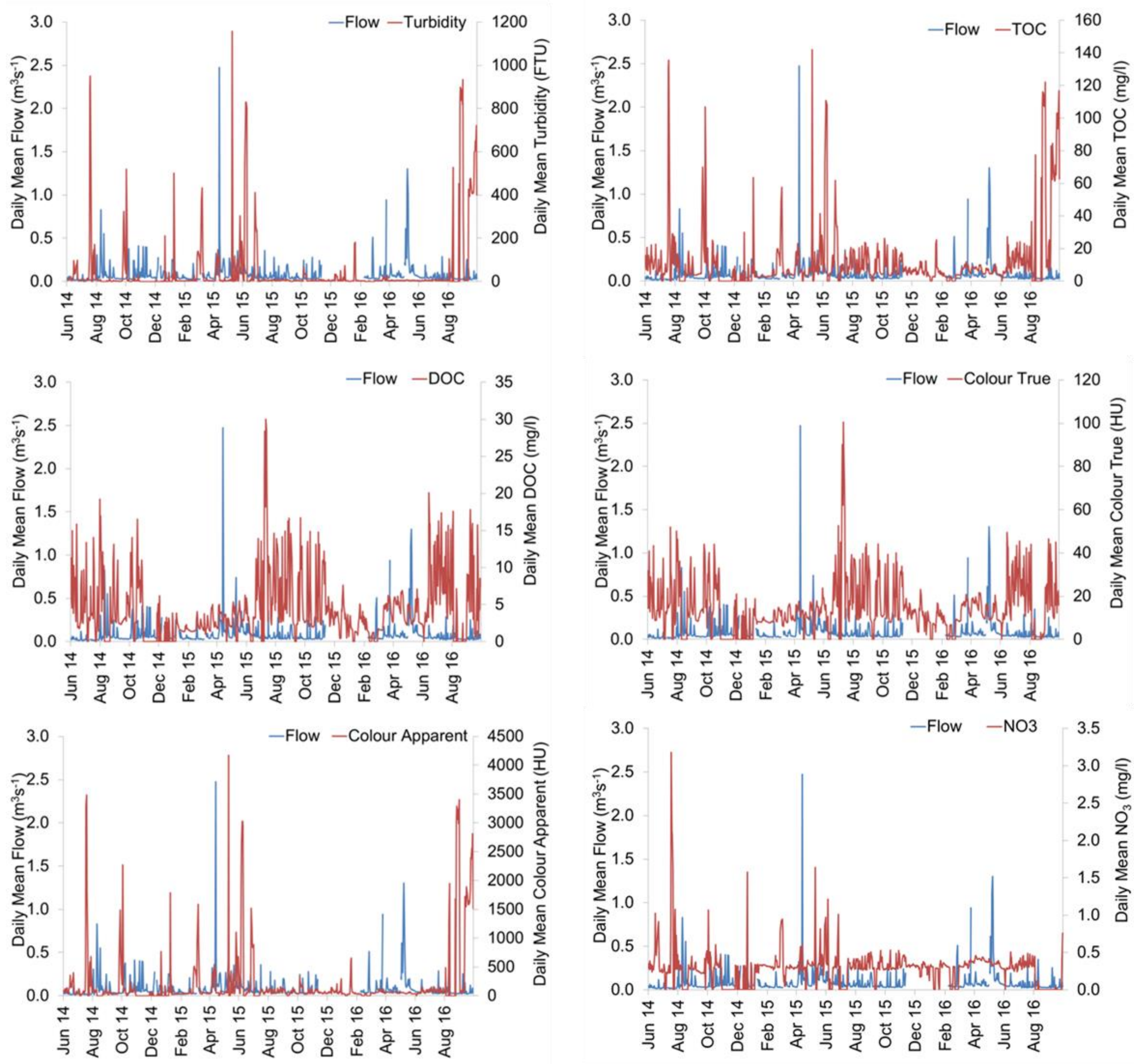


Figure 5-27: Spectro::lyser data graphed

Daily mean, omitting suspect data, shown for turbidity, total organic carbon (TOC), dissolved organic carbon (DOC), colour true, colour apparent and nitrate.

The data for the parameters monitored vary between years. The mean turbidity from the Mòine Mhór tributary in 2014, 2015 and 2016 was 47 Formazin Turbidity Units (FTU), 42 FTU and 68 FTU respectively. At most times, turbidity remains low but during events it can increase. The mean DOC from the Mòine Mhór tributary in 2014, 2015 and 2016 was 5.8 mg/l, 4.9 mg/l and 5.2 mg/l respectively. A concentration of DOC of ~ 5 mg/l represents a baseline level for the stream. The seasonal pattern of increased DOC concentrations during the summer and lower concentrations during the winter months is evident in Figure 5-27, a trend also observed in Koehler and colleagues study of an Atlantic blanket bog in south western Ireland (Koehler *et al.*, 2009). This seasonal pattern has further been observed in Dawson and colleagues study who reported that the seasonal variance is attributable to the higher temperatures driving biological activity which in turn increases the decomposition of available organic matter and solubility of DOC (Dawson *et al.*, 2008). The mean TOC in 2014, 2015 and 2016 was 15 mg/l, 12 mg/l and 17 mg/l respectively which appears to be the baseline level. The mean nitrate concentration in 2014, 2015 and 2016 was 0.42 mg/l, 0.35 mg/l and 0.33 mg/l respectively. These concentrations (~0.3 mg/l) indicate nitrogen retention within the catchment vegetation and soils at a slightly lower rate than found in Soulsby and colleague study streams in the Cairngorms where values were mostly below 0.1 mg/l (Soulsby *et al.*, 2001). Colour values for true were 20 HU, 17 HU and 16 HU in 2014, 2015 and 2016 respectively. Colour apparent values for 2014 (221 HU), 2015 (190 HU) and 2016 (298 HU) remained comparable with each other.

Across the full dataset, seasonally, the highest maximum values for turbidity (1158 FTU), TOC (135 mg/l), and colour apparent (4171 HU) occurred in spring. The highest maximum values for nitrate (3.18 mg/l), DOC (30 mg/l) and colour true (100 HU) occurred in summer. Higher nitrate concentrations were generally experienced after spring snowmelt or after warm temperatures. The reported mean values across the seasons have been summarised in Table 5-16 below and display the variations with winter noted with the lowest values.

Table 5-16: Mean spectro::lyser values across the seasons

The seasons have been defined as previously outlined in Table 5-4 and included two complete spring, autumn and winter seasons and three summer seasons across 2014 to 2016.

Parameter	Spring	Summer	Autumn	Winter
Turbidity (FTU)	34	76	63	27
Nitrate (mg/l)	0.4	0.4	0.3	0.3
TOC (mg/l)	10	19	18	7.0
DOC (mg/l)	3.8	7.5	5.8	2.5
Colour Ture (HU)	14	23	19	11
Colour Apparent (HU)	152	334	290	120

These readings indicate a loss of carbon from the Mòine Mhór streams and the turbidity values indicate an export of particulate matter down the streams. The reliability of the results due to cleaning has been highlighted previously but the data does indicate a net export of organic carbon through the water environment.

5.7.2 Spot sampling

Alongside the continuous monitoring, the spectro::lyser had the capacity to double up as a 'lab instrument'. The opportunity was taken on 15 occasions to take the instrument out of the water, place it on the bank side, clean it and use it to analyse the collected samples for the other monitored catchments to allow comparisons between sites. This was achieved by placing a plastic cup like cylinder over the spectro::lyser which allowed a small amount of the sampled stream water to be poured into the optical window measuring area. Samples were analysed for turbidity, nitrate, TOC, DOC, colour true and colour apparent. Results from the monitored streams are displayed in Figure 5-28. A total of 74 data readings are included from across 15 different sampling dates from the eight monitored streams sampled on the Mòine Mhór. This value is slightly lower than one may expect due to the difficulties associated with using the spectro::lyser as a lab instrument in the field environment.

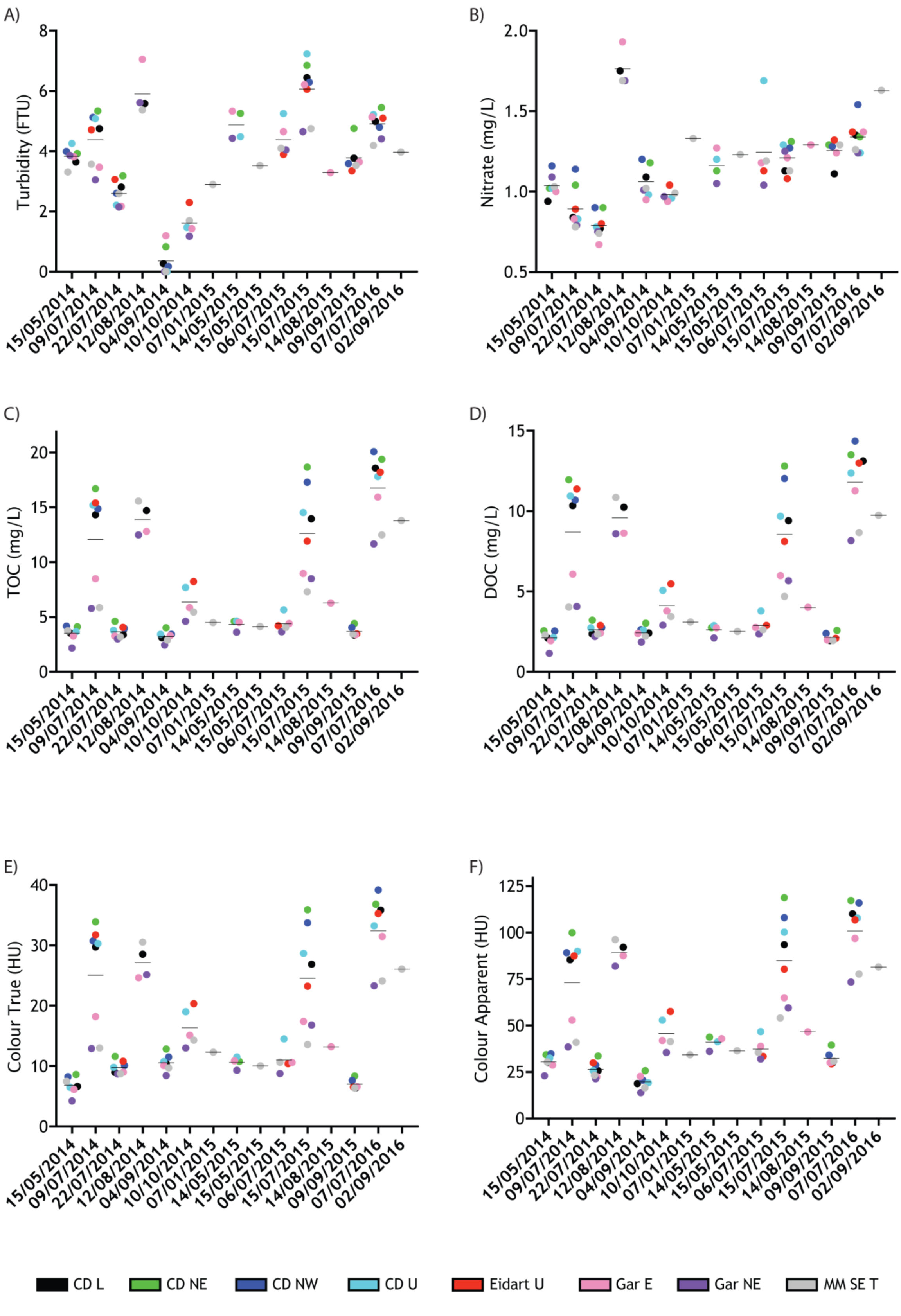


Figure 5-28: Manual spectro::lyser measurements

On 15 occasions the water samples collected across the monitored catchments were analysed in the field using the spectro::lyser for turbidity (A), nitrate (B), TOC (C), DOC (D), colour true (E) and colour apparent (F). The mean value across all eight samples streams is shown by the straight grey line visible on each sample analysis date.

To ascertain the reliability in relation to the continuous DOC data collected from the spectro::lyser (located in the field) and from the spot sampling (again *in-situ* by using the spectro::lyser), DOC was also determined in water samples in the laboratory environment. Ideally this would have been calculated for each of the samples collected but unfortunately, the facilities for testing DOC were not available at the University of Dundee Geography laboratory and therefore other options were sourced. Through a pre-existing collaboration access was granted to CEH Edinburgh Bush laboratory to analyse a number of samples using their LabTOC analyser, which is capable of measuring DOC. This served the purpose of testing that the values recorded in the field were similar to those reported through laboratory analysis. The results are graphed in Figure 5-29.

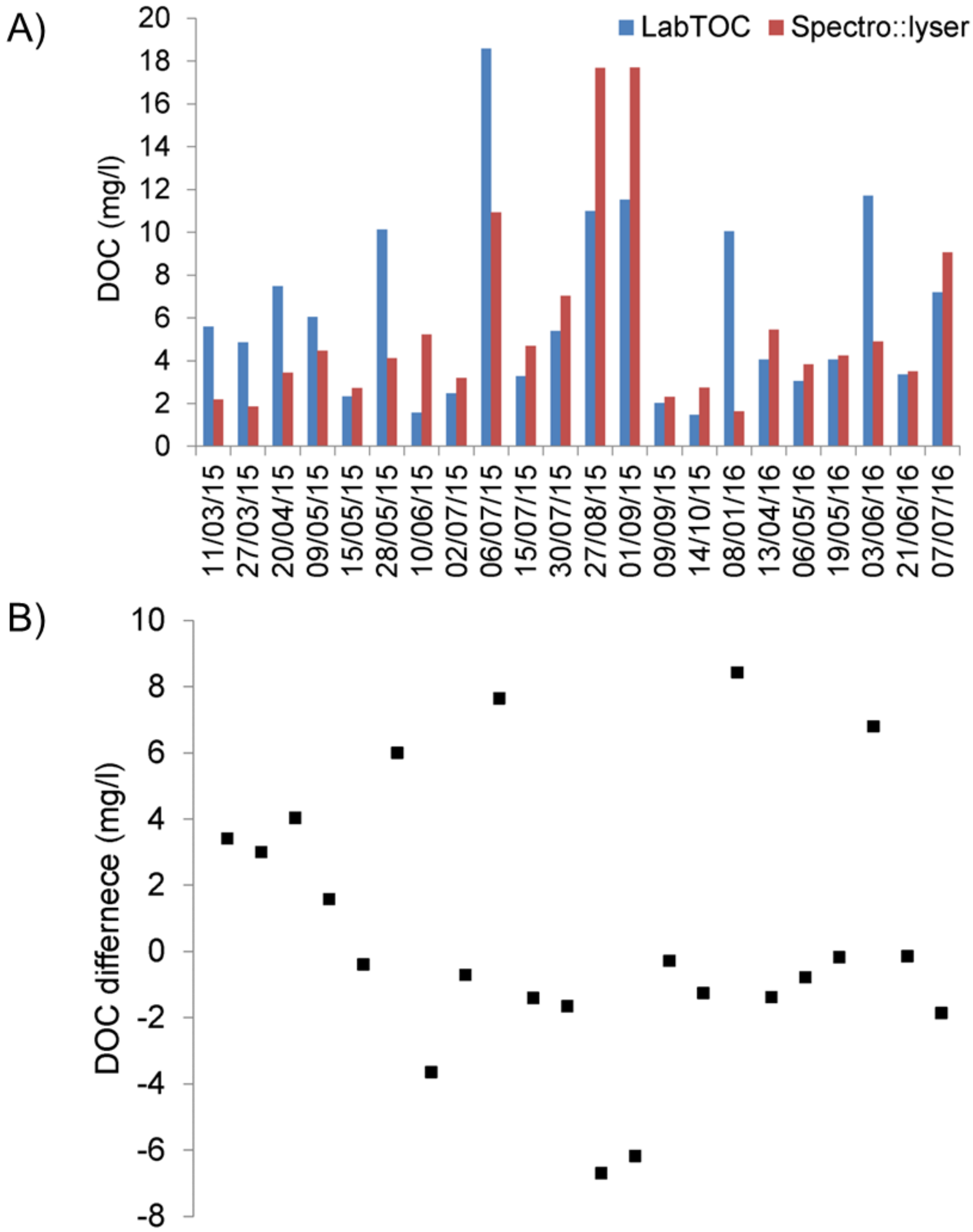


Figure 5-29: Dissolved organic carbon (DOC) data comparison

DOC is displayed as a bar graph with each measurement plot (A) and a scatterplot of differences between the two values (B). DOC data taken from the spectro::lyser located in the field and DOC data from water samples collected at the same time and analysed in the LabTOC at CEH, Edinburgh. The closest time was picked when taking values from spectro::lyser dataset, there was sometimes a bit of a gap due to the collection of water samples at the same time as the probe was downloaded.

The difference in results was calculated by taking the CEH LabTOC value away from the spectro::lyser value. The mean difference across the 22 occasions on which DOC was determined in Mòine Mhór south east tributary samples in the laboratory against the spetro::lyser was 0.65 mg/L. The maximum difference was 8.43 mg/L. This may be due to the slight difference in DOC from the time the water sample was taken and the time the DOC reading was taken from the spectro::lyser after it had been cleaned and downloaded. The difference might also be attributable to DOC deterioration in water samples between collection in the field and the LabTOC analysis. Another reason for the differences may be that the LabTOC directly measures the DOC concentration whereas the spectro::lyser infers the concentration by light spectroscopy. Again the measurements highlight an export of DOC from the streams draining the Mòine Mhór.

The sprecto::lyser was useful for continuously monitoring the water quality across the study period. The sensor would suffer with a build of grime resulting in some artificially high readings which had to be removed from the dataset. From the remaining results, the median turbidity was between 4-5 FTU however the mean turbidity was much higher at 41-68 FTU. This indicates that high flows can result in quite a lot of material being exported down a relatively small catchment area. The organic carbon results captured from the spectro::lyser allow for estimates on carbon exports to be calculated as presented in Section 5.11. Another instrument which allowed for the monitoring of the water quality while not present on site was the autosampler, the results of which are presented in Section 5.8 below.

5.8 High flow events

In the UK uplands floods are typically caused by additional rainfall or snowmelt onto an already saturated catchment. The largest floods are usually caused by both rainfall and snowmelt (Black and Burns, 2002; Gilvear *et al.*, 2002). Of interest for this study are the higher flow events that took place over the duration of the sampling period. During flood events a lot of changes can occur and as a result concentrations of dissolved organic carbon export can increase. The successful capturing of high flow events proved challenging due to the distance and remote nature of the study site and access issues but, despite this, some were captured.

The flow and precipitation results presented already have been referred back to in order to identify periods of interest for potential event analysis. The highest level on record (since Dec 1992) for the River Feshie (Section 5.2) was on the

30th December 2015 with a water level of 2.72 m at 1215 GMT. From the mean gauged daily flows (Section 4.5) the maximum values across the years highlighted that the 7th March 2015 was of interest (highest peak flow at Caochan Dubh lower, Eidart upper and Mòine Mhór south east tributary). The other streams highlighted that the 16th March 2014 (Caochan Dubh upper), 2nd December 2015 (Garbhlach north east) and 25th January 2016 (Garbhlach east and Caochan Dubh north west) were also worth exploring. With reference to the Met Office data (Section 5.5) the month of December 2013 was the wettest in the UK since 1910. In August 2014, Hurricane Bertha was also notable causing high winds and heavy rainfall. Furthermore, in 2015, December had greater than 200 % total precipitation compared to the 1981-2010 average.

High winds and rain were the result of the remnants of ex-hurricane Bertha and impacted across the UK from the 10th to 11th August 2014. The SEPA Feshie Gauging Station recorded a level of 2.42 m on the 11th August 2014 with the mean level on record being 0.78 m. A site visit on 12th August 2014 confirmed that the river level was high (Figure 5-30). The event peak occurred the day prior to the visit.

Figure 5-30: River fords on the morning of Tuesday 12th August 2014

From left to right; looking upstream from the River Feshie ford to the Carnachiun Bridge which was swept away by the Feshie in spate (flood) on the 3rd of September 2009, it is yet to be replaced. On this day the Feshie river level was too high to successfully cross. Centre photograph is the Auchlean (Pony) Bridge which represents the last crossing in upper Glen Feshie. Right hand photograph shows the Garbhlach stream which also must be forded when ascending the Mòine Mhór from Auchlean.

Three streams were gauged on the Mòine Mhór on the 12th August 2014 and represented high level gauging results. The results collected provided the upper flow values in the rating curve shown in Figure 5-11 for Caochan Dubh lower (0.84 m^3 s^{-1}), Garbhlach east (0.39 m^3 s^{-1}) and Garbhlach north east (0.14 m^3 s^{-1}). Reported mean flow gauging values for Caochan Dubh lower (0.26 m^3 s^{-1}), Garbhlach east (0.11 $m^3 s^{-1}$) and Garbhlach north east (0.04 $m^3 s^{-1}$) highlight the significance of this event. Flow at Garbhlach north east burst out of its bank whereas flows at Caochan Dubh lower and Garbhlach east were still contained within their banks. The water samples were collected after the peak of the event therefore gauging results for flow values could have been even greater if measured at the peak of the event. The data collected from the TBR on site (Meur Shuas) confirm that samples were collected on the falling limb of the event. Daily precipitation totals were calculated from 0900 GMT on the date given and 0859 GMT on the following day (Scottish Environment Protection Agency, 2017). A total of 88.8 mm and 24.6 mm were recorded at the peak of the event, 10th and 11th August 2014 respectively. On the sample date of the 12th August 2014, 4.8 mm fell on an already saturated catchment that had full and fast flowing rivers.

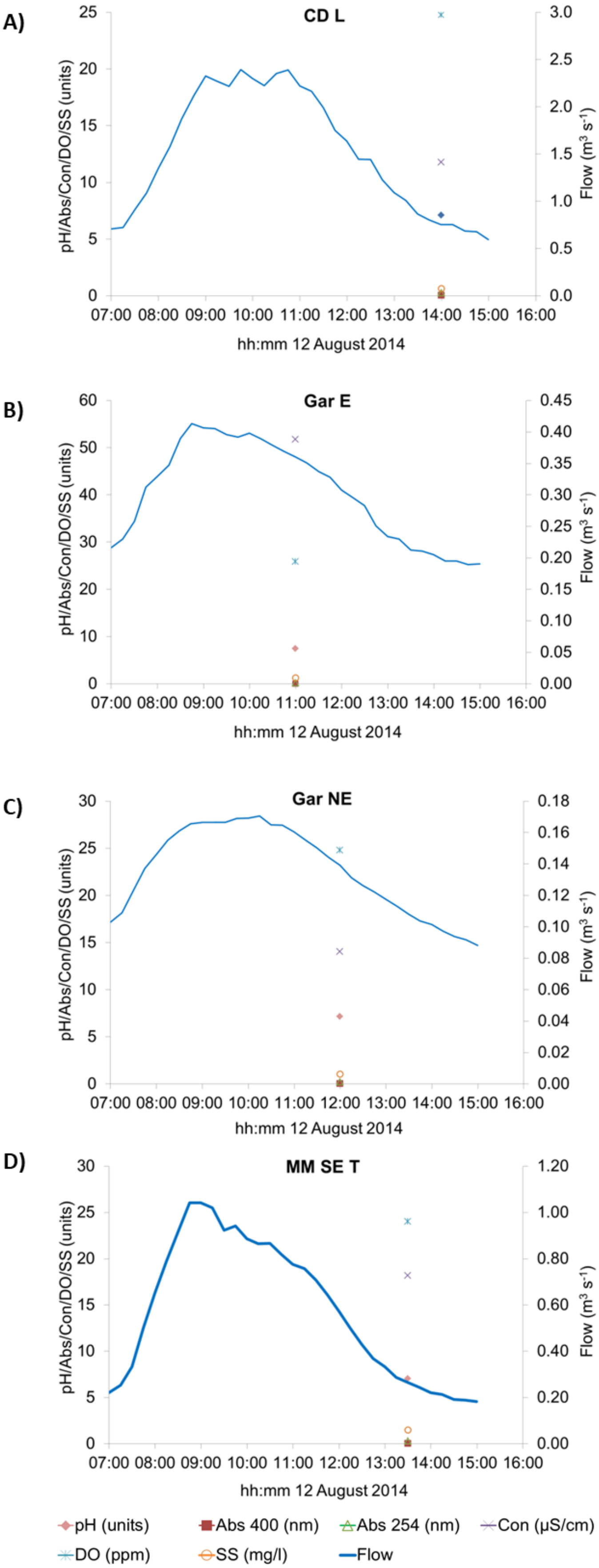


Figure 5-31: Flow and water quality on the 12th August 2014

Water samples were collected and analysed in the laboratory at four of the monitored streams; CD L (A), Gar E (B), Gar NE (C) and MM SE T (D). No spectro::lyser data is available for this period as it was washed downstream at the peak of the event on the 10th August 2014 at 2300 GMT.

The precipitation data collected (Section 5.5) allows the water quality results to be explored with reference to the hydro-meteorological site specific conditions of the Mòine Mhór. The monthly precipitation totals recorded for December 2013 (110.6 mm), December 2014 (87 mm) and December 2015 (452.4 mm) at Meur Shuas indicate that the winters of 2013 and 2015 were wetter than the precipitation mean for the month. Data from the Chomhraig TBR also confirms that for the Glen Feshie monitoring network, December 2015 (279.8 mm) was wetter than December 2013 (216.8 mm).

The highest daily mean flows were recorded at the Caochan Dubh lower, Eidart upper and Mòine Mhór south east tributary on the 7th March 2015 (Figure 5-12). It is not believed that these peaks were caused by a high magnitude rainfall event since Meur Shuas recorded a total precipitation of 10.8 mm on the 7th March 2015. A study site visit on the 27th February and 11th March 2015 confirmed that the streams and the study site were snow covered therefore the stream level would not have been as responsive to this rain/snow falling onto the catchment. However, the stream temperature on the 6th March 2015 did rise above zero (daily mean of 1.32 °C) indicating that snow melt could have been responsible for the peak in river level and daily flow values seen on the 7th March 2015. The melt does not appear to have been sustained with the stream temperature returning to a mean daily temperature value of 0.28 °C the following day.

Sample Date	Filter Paper	Suspended Sediment
MM SE T 01/09/2015 14:15		93.4 + 8.1 mg/L
Eidart U 03/09/2015 08:50		1.8 mg/L
CD NW 03/09/2015 09:30		7 mg/L
CD NE 03/09/2015 09:35		29.5 mg/L
CD U 03/09/2015 09:45		11.6 mg/L
Gar E 03/09/2015 10:00		58.4 mg/L

Figure 5-32: Filter paper photographs

Note the variation in suspended sediment concentration noted across the Eidart U, CD NW, CD NE, CD U and Gar E samples which were all collected within 2 hours of each other on the 3rd of September 2015. The MM SE T sample was not available for the 3rd September 2015 but a sample collected two days prior on the 1st September 2015 shows the elevated concentrations of sediment recorded in the stream.

Generally, the filter papers would remain pale/clean after filtration of the water sample and the calculated suspended sediment concentration would be close to or at 0 mg/L. Figure 5-32 shows filter papers for water sample periods where higher amounts of material were trapped on the filter paper and when two filter papers were required to filter one sample at the Mòine Mhór south east tributary on the 1st September 2015. A concentration of 93.4 mg/L of suspended sediment at the Mòine Mhór south east tributary represented the maximum concentration recorded across the streams and project timeline. The values shown in Figure 5-32 represent the upper values of suspended sediment concentrations captured at the monitored catchments.

The maximum suspended sediment concentrations at the Caochan Dubh lower and Eidart upper site were recorded on the 27th August 2015 (Figure 5-33). The sample collected at the Eidart upper site was collected at 08:15 GMT and was captured at the peak of the event corresponding with a flow value of 0.37 $m^3 s^{-1}$ (mean flow is normally 0.16 $m^3 s^{-1}$, Table 5-8). The rest of the streams were sampled after this point in time (between 11:55 GMT and 15:10 GMT) and thus represent the receding limb of the hydrograph (example Caochan Dubh lower shown in Figure 5-33). However, these samples still represent the maximum peaks recorded for absorbance at 400 nm for the Eidart upper, Caochan Dubh lower, Caochan Dubh north west, Caochan Dubh upper, Garbhlach north east and Mòine Mhór south east tributary sites across the sampling period (Figure 5-23).

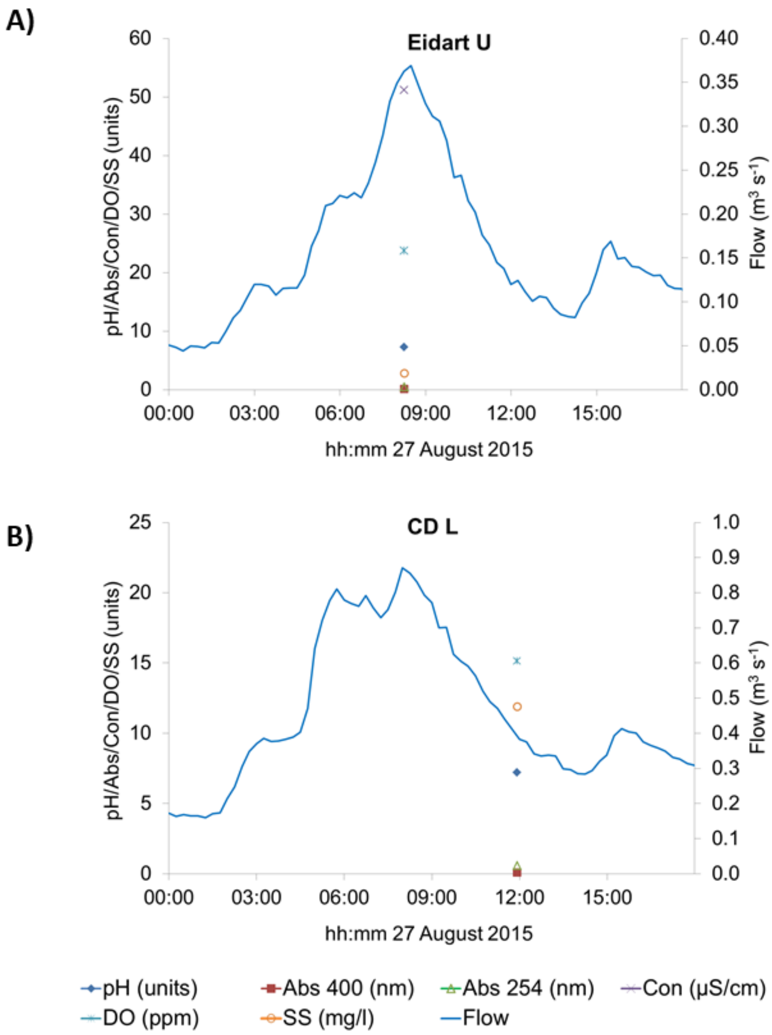


Figure 5-33: Flow and water quality on the 27th August 2015

Sample collected at peak flow at the Eidart U (A). The other streams were sampled on the falling limb as shown in CD L (B) however the values reported still represented maximum values with for colour (absorbance) and particulates (suspended sediment).

5.8.1 Autosampler

To maximise the chances of capturing water samples during high flow conditions, an autosampler was placed on the Mòine Mhór south east tributary adjacent to the spectro::lyser and was set-up to start sampling when triggered by a level switch. In addition, another autosampler was set up at the Garbhlach east stream next to the gauging and sampling location. The events sampled have been summarised in Table 5-17 and include three events from the Garbhlach east autosampler and eleven events from the Mòine Mhór south east tributary autosampler. Dependant on site access and visual checks for a change in water colour or presence of suspended sediment, some of the samples collected were taken back to the laboratory for further analysis while others were poured out to allow for further chances for successful events to be captured. At the Mòine Mhór south east tributary site, the trial and error of successfully trying to capture an event and work out the desired height to set the level switch at resulted in the duration of the autosampler being set at differing time intervals ranging from 12 hours (sample every 30 mins) to 24 hours (one sample taken daily covering a period of 24 days).

Table 5-17: Summary of events sampled

Rainfall values are taken from Cairngorm ECN AWS data. The peak flow and highest daily rainfall is considered in the time range of the respective event date listed. 5 day total antecedent rainfall is the total daily rainfall 5 days prior to the event start date. Samples analysed in laboratory related to the number of samples collected that were taken back to the laboratory for analysis. The spectro:;lyser could be used in the field environment and some of the samples collected by the autosampler were analysed in the field using the spectro::lyser. Comments relate to field notes taken at the time and indicate success or issues noted with the collection of each respective event sampled.

Location	Event Date / Time (GMT)	Duration	Number of water samples collected	Peak Flow ($m^3 s^{-1}$)	Highest Daily Rainfall (mm)	5 Day Total Antecedent Rainfall (mm)	Samples Analysed in Laboratory	Max SS (mg/L)	Max Abs400 (nm)	Spectro::lyser Analysis	Comment
Gar E	10/06/14 11:50 - 11/06/14 02:50	15 hours	16	0.037 $m^3 s^{-1}$ on 10/06/14 at 20:15	5.25 mm on 10/06/14	37.36 mm	16	1.3 mg/l on 11/06/14 at 02:50	0.056 nm on 10/06/14 at 11:50	Not analysed	Autosampler stopped part-way through programme as ran out of charge, collected 16 samples. Heavy rain noted night of 10th as had overnight stay from 10th to 11th to trial deployment.
Gar E	31/07/15 11:20 - 05/08/15 11:20	5 days	6	0.197 $m^3 s^{-1}$ on 03/08/15 at 11:15	6.45 mm on 01/08/15	26.67 mm	6	186 mg/l on 05/08/15 at 11:20	0.089 nm on 04/08/15 at 11:20	Max Turbidity of 7.18 FTU and DOC of 15.55 mg/l on 04/08/15 at 11:20	Site visit on 14th Aug 2015, discovered 6 bottles filled up then overfilled bottle 7 and stopped. Battery changed and programme re-set to take daily samples starting at 7 am on 15th Aug 2015.

Gar E	15/08/15 07:00 - 22/08/15 07:00	7 days	7	0.869 m^3 s^{-1} on 15/08/15 at 08:45	15.23 mm on 15/08/15	13.48 mm	0	N/A	N/A	Not analysed	Site visit on 27th Aug 2015, autosampler still not working properly, took 7 samples then overflowed. No colour change evident in samples, poured out. Checked again on 14th Oct 15, battery working but still not working properly. Left on site into Nov but no further events captured.
MM SE T	10/06/14 13:10 - 11/06/14 01:10	12 hours	13	0.045 m^3 s^{-1} on 10/06/14 at 19:45	5.25 mm on 10/06/14	37.36 mm	13	2.5 mg/l on 10/06/14 at 21:10	0.067 on 10/06/14 at 22:10	Not analysed	Autosampler battery ran out of charge one 12ah was not enough would have needed two. Organised for next visit.
MM SE T	collected on 28/05/15, trigger time for collection of samples unknown	3 hours	3	-	-	-	3	30.4 mg/l from Auto 1	0.019 nm from Auto 1	Not analysed	Snowy and windy conditions on site visit on 28th May - power had failed on autosampler, only managed to take 3 samples, unable to determine start date/time. Analysed as Auto 1, Auto 2 and Auto 3.

MM SE T	10/06/15 15:15 - 04/07/15 15:15	24 days	24	1.687 m^3 s^{-1} on 26/06/15 at 17:15	11.72 mm on 13/06/15 and 22/06/15	7.63	0	N/A	N/A	Max Turbidity of 4.39 FTU and max DOC of 10.6 mg/l on 22/06/15 at 15:15 (Auto 12).	On a site visit on the 10th June 2015 the autosampler was set to take a daily sample at 14:15. Site visit on the 6th July 2015, discovered Auto 1, 2 and 3 had started re-filling with another sample so had to pour out, perhaps due to programming error. Other 21 samples analysed in spectro::lyser.
MM SE T	16/07/15 06:00 - 30/07/15 06:00	14 days	15	2.429 m^3 s^{-1} on 17/07/15 at 07:45	18.96 mm on 17/07/15	8.85 mm	1 (Auto 2)	20.7 mg/l on 17/07/15 06:00	0.061 nm	Max Turbidity of 22.75 FTU on 17/07/15 at 06:00. Max DOC of 13.57 mg/l on 19/07/15 at 06:00	All samples collected were analysed in the spectro::lyser, only highest turbidity sample (Auto 2) taken back to laboratory.

MM SE T	03/08/15 13:53 - 04/08/15 01:23	11.5 hours	24	0.079 m^3 s^{-1} on 03/08/15 at 14:00	2.57 mm on 03/08/15	24.28 mm	7 (Auto 1 - Auto 7)	1.3 mg/l on 03/08/15 14:23	0.076 nm on 03/08/15 13:52	Max Turbidity of 7.78 FTU on 03/08/15 at 15:23 (Auto 4). Max DOC of 16.17 mg/l on 03/08/15 at 14:23 (Auto 2)	Site visit on 14th Aug 2015, discovered that autosampler had been triggered by stage trigger on Mon 3rd Aug and took 24 samples at intervals of 30 minutes. All samples were analysed in the spectro::lyser but didn't capture an event, took Auto 1-7 back to lab for analysis. Tried to re-set autosampler to trigger at high flow.
MM SE T	01/09/15 14:04 - 02/09/15 07:04	17 hours	24	0.582 m^3 s^{-1} on 01/09/15 at 17:45	15.64 mm on 01/09/15	12.38 mm	0	N/A	N/A	Max Turbidity of 34.67 FTU on 01/09/15 at 16:04 (Auto 4). Max DOC of 17.37 mg/l on 01/09/15 at 14:34 (Auto 2)	Site visit on 1st Sep 2015, grab sample taken at 14:15 on 01/09/15, mean SS of 58.6 mg/l and abs 400 nm of 0.085 nm. Analysed samples in spectro::lyser on site visit on 9th Sep 2015.
MM SE T	20/05/16 02:00 - 24/05/16 08:00	4 days	24	0.403 m^3 s^{-1} on 21/05/16 at 12:15	0 mm	0.98 mm	4	2.9 mg/l on 21/05/16 08:00	0.039 nm 21/05/2016 08:00:00	Not analysed	Site visit on 3rd Jun 2016 and noted for next time to bring up bottles to collect what is in the autosampler and set

											up level switch again. Visited again on 21st Jun and reset level switch. Auto 3, 8, 14 and 20 taken back to lab for analysis.
MM SE T	10/07/16 15:56 - 10/07/16 21:54	6 hours	24	0.668 m^3 s^{-1} on 10/07/16 at 15:45	4.10 mm on 10/07/16	12.68 mm	6	2.7 mg/l on 10/07/16 16:11	0.086 nm on 10/07/16 18:56	Not analysed	Site visit on 4th Aug 2016, autosampler had been triggered by level switch on 10th Jul. Auto 1, 2, 6, 13, 20 and 23 taken back to lab for analysis. Programmed sampler to start sampling on 4th Aug at 13:50 as river levels were high when on site.
MM SE T	04/08/16 13:44 - 05/08/16 01:14	11.5 hours	24	0.899 m^3 s^{-1} on 04/08/16 at 14:00	6.44 mm on 04/08/16	14.04 mm	0	N/A	N/A	Max Turbidity of 9.5 FTU and max DOC of 18.7 mg/l on 04/08/16 at 13:44 (Auto 1).	Site visit on 2nd Sep 2016, emptied autosampler and analysed on spectro::lyser. Re-set on level switch.

MM SE T	08/09/16 11:50 - 08/09/16 23:20	11.5 hours	24	0.345 m^3 s^{-1} on 08/09/16 at 11:45	0.39 mm on 08/09/16	0 mm	0	N/A	N/A	Max Turbidity of 10.3 FTU on 08/09/16 at 11:50. Max DOC of 23.9 mg/l on 08/09/16 at 12:50	Site visit on 30th Sep 2016, analysed samples in the spectro::lyser (Auto 1, 3, 6, 9, 12, 15, 19, 21, 23 and 24). Re-set on level switch.
MM SE T	31/10/16 10:30 - 31/10/16 11:30	1 hour	3	-	-	-	3	7.6 mg/l on 31/10/16 10:30	0.116 nm on 31/10/16 10:30	Not analysed	Site visit on 31st Oct 2016, autosampler had triggered at 10.30 am and was about to start bottle 3 when arrived. Last visit, removed equipment from site.

Water quality results from samples collected from an event sampled at the Mòine Mhór south east tributary from using the autosampler are shown in Figure 5-34. An increase in flow corresponds with an increase in suspended sediment, absorbance at 400 nm, DOC and turbidity, with no apparent delay in response between flow and the monitored parameters. The DOC peaked at 9.3 mg C L^{-1} before falling to 4.1 mg C L^{-1}. At the same point in time, turbidity peaked at 14.5 NTU before falling to 4.1 NTU.

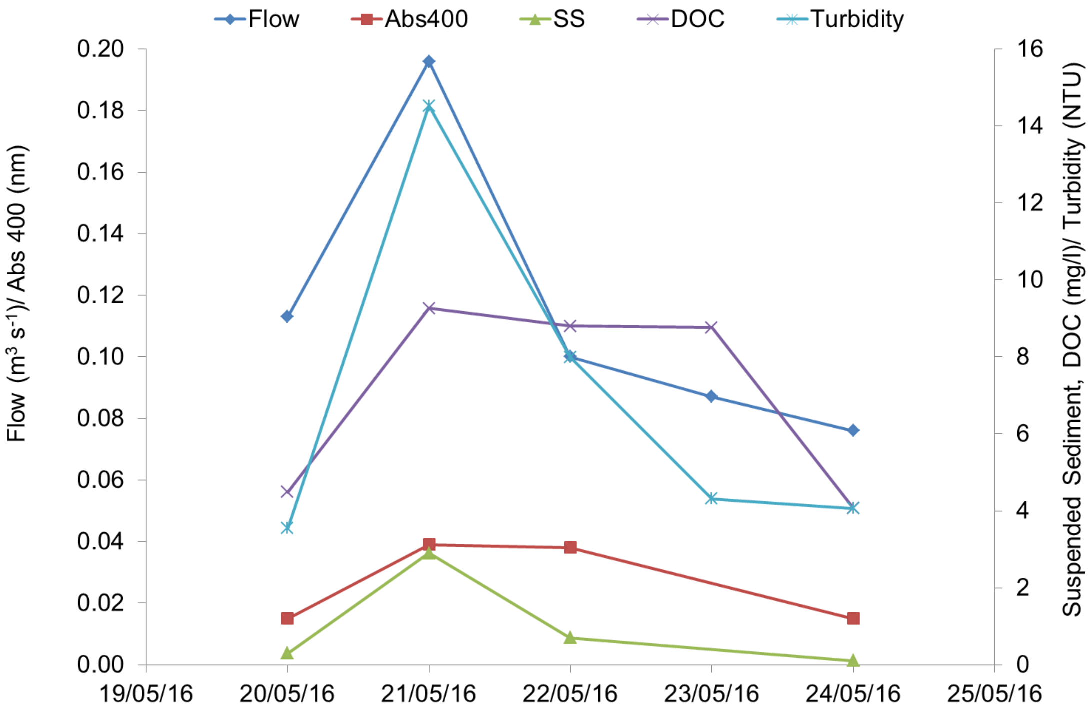


Figure 5-34: Autosampler and spectro::lyser results from MM SE T

MM SE T water samples taken from the auto sampler on the 20th May 2016 at 02:00, 21st May 2016 08:00, 22nd May 20:00 and 24th May at 08:00 GMT. The DOC and turbidity data has been taken from the spectro::lyser, which was positioned in the stream next to the autosampler.

Typically, the concentrations of DOC peak at ~ 15 - 20 mg C L^{-1} during these high flow events. There appears to be a positive relationship between flow with DOC, turbidity, absorbance and suspended sediment during events as displayed in Figure 5-34. During these events surrounding peat/sediment is washed into the streams giving a corresponding increase in detectable colour and suspended sediment. The events captured indicate that high flows do have an impact on the water quality parameters. The increased values of the water quality parameter relative to the headwater environment tended to occur on the day or the day after the highest flow was recorded.

In relation to the Garbhlach east autosampler results (Table 5-17), the peak flow value on the 3rd August 2015 of 0.197 m^3 s^{-1} was of interest as it lies close to the Q10 flow percentile (Table 5-8) highlighting that the water chemistry results will be reflective of the upper limits expected within this stream. From the Mòine Mhór south east tributary autosampler results, seven of the peak flow values were greater than the mean flow for the stream (Table 5-8) again indicating that some of the results captured can be considered reflective of the water chemistry response to high flows.

5.9 Inorganic carbon

The measurement of dissolved inorganic carbon (DIC) assists in capturing the complete aqueous carbon budget. Dissolved carbon dioxide (CO_2) and methane (CH_4) contribute to the carbon loss from aquatic systems in peat-dominated environments.

To quantify DIC concentrations two methods were used. Gas samples were taken from the stream using a standardised 'headspace' method and analysed for dissolved CO_2 and CH_4 by gas chromatography through a collaboration set up with CEH, Edinburgh. Over the same duration, continuous dissolved CO_2 concentrations were derived from a Non-Dispersive Infra-Red (NDIR) sensor (Vaisala GMP343 Carbocap with MI70 data reader/logger). This instrument is normally used for sampling in air but was adapted for use in the water environment. The combination of methods allowed the temporal variability in DIC to be quantified and the amount of carbon loss through DIC in water runoff to be estimated from the Mòine Mhór.

The Vaisala Carbocap instrument was installed at the Mòine Mhór south-east tributary site on 11th March 2015 (under approximately 1 m of snowpack). Data was logged at 30-minute intervals from that date (with some gaps due to instrument/logger failure) until 4th December 2015 when the instrument was dislodged and washed away due to snowpack movement in a storm event. Despite numerous searches well downstream the instrument was not located again. Although less than a complete year in duration, the logged results allow a good estimation of the inorganic carbon budget from a stream draining the Mòine Mhór. Figure 5-35 below shows the raw (uncorrected for the effect of pressure on sensor output) data logged by the Vaisala Carbocap over a one year period.

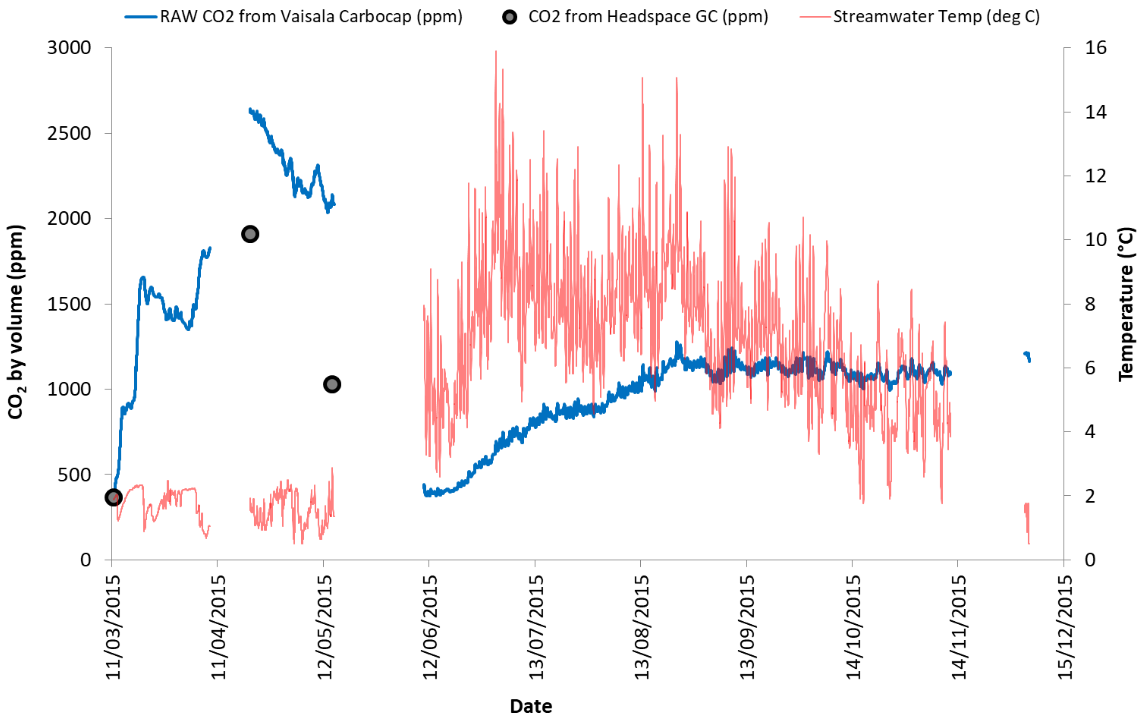


Figure 5-35: Mòine Mhór SE tributary dissolved CO_2 measurements from Vaisala Carbocap and headspace samples data

The probe was situated in the Mòine Mhór SE tributary which drains the main stream draining the plateau, the Caochan Dubh site. The data gathered has been plotted based on the length of the dataset.

Results of headspace sampling analysis were compared to logged data (see Figure 5-35 above). Headspace analysis results for dissolved CO_2 matched the instrument output in trend but the samples from 20th April 2015 and 15th May 2015 contained lower dissolved CO_2 concentrations than were detected by the sensor in the field. Headspace sampling was infrequent with a prolonged time delay before analysis of samples (due to logistics and availability of GC resource). Further headspace samples were taken in 2015 but not analysed due to a breakdown and unavailability of the GC machine. Due to the small size of the headspace sample dataset it is not possible to determine whether the Carbocap NDIR sensor remained in calibration throughout the data collection period or whether there might have been any deterioration in accuracy of the sensor over time due to moisture ingress/condensation.

Time series of dissolved CO_2 values were plotted with stream temperature and discharge (Figure 5-36) to examine if there was any correlation between them.

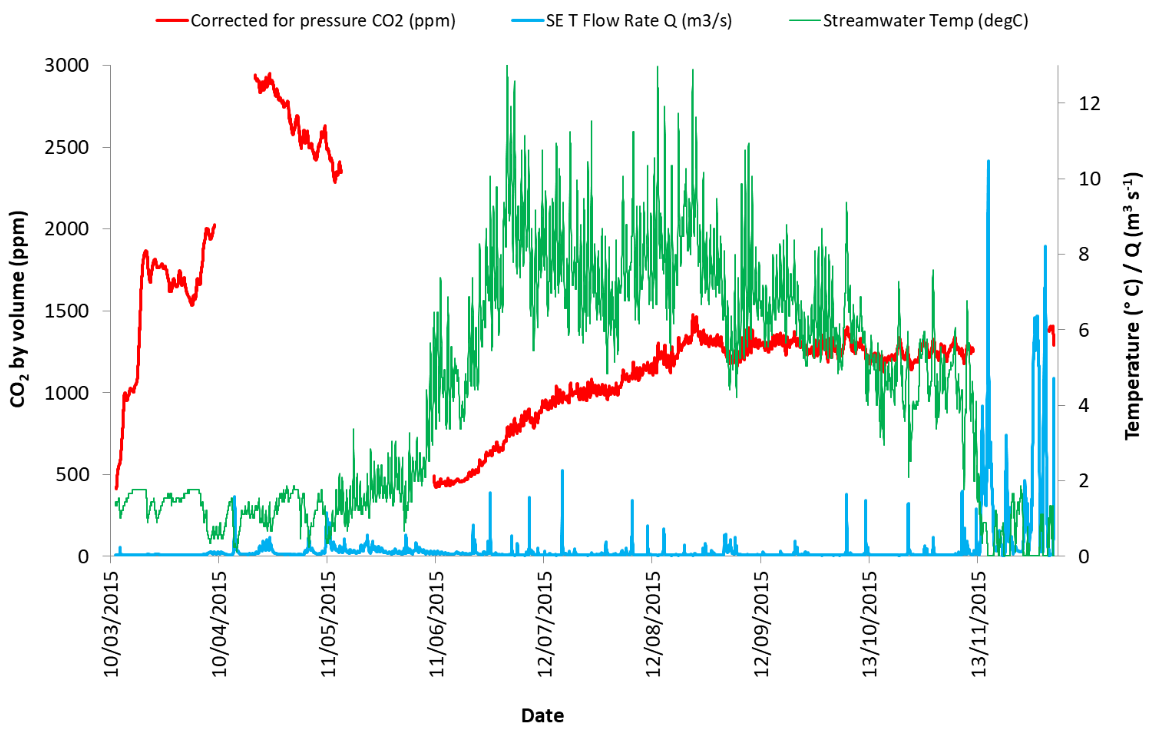


Figure 5-36: Time series of dissolved CO_2 stream temperature and flow rate in MM SE T in March-December 2015

The dissolved CO_2 measurements from the Vaisala Carbocap have been corrected for pressure.

Seasonally concentrations of dissolved CO_2 seem to be minimal in spring/early summer, increasing slowly throughout summer, autumn and early winter to a peak in late winter/early spring before rapidly falling. The peak concentrations of dissolved CO_2 seem to correspond with snowpack melting. Temperature has a short-term effect on dissolved CO_2 concentrations as does flow rate, as can be seen in plots over a shorter period as displayed in Figure 5-37.

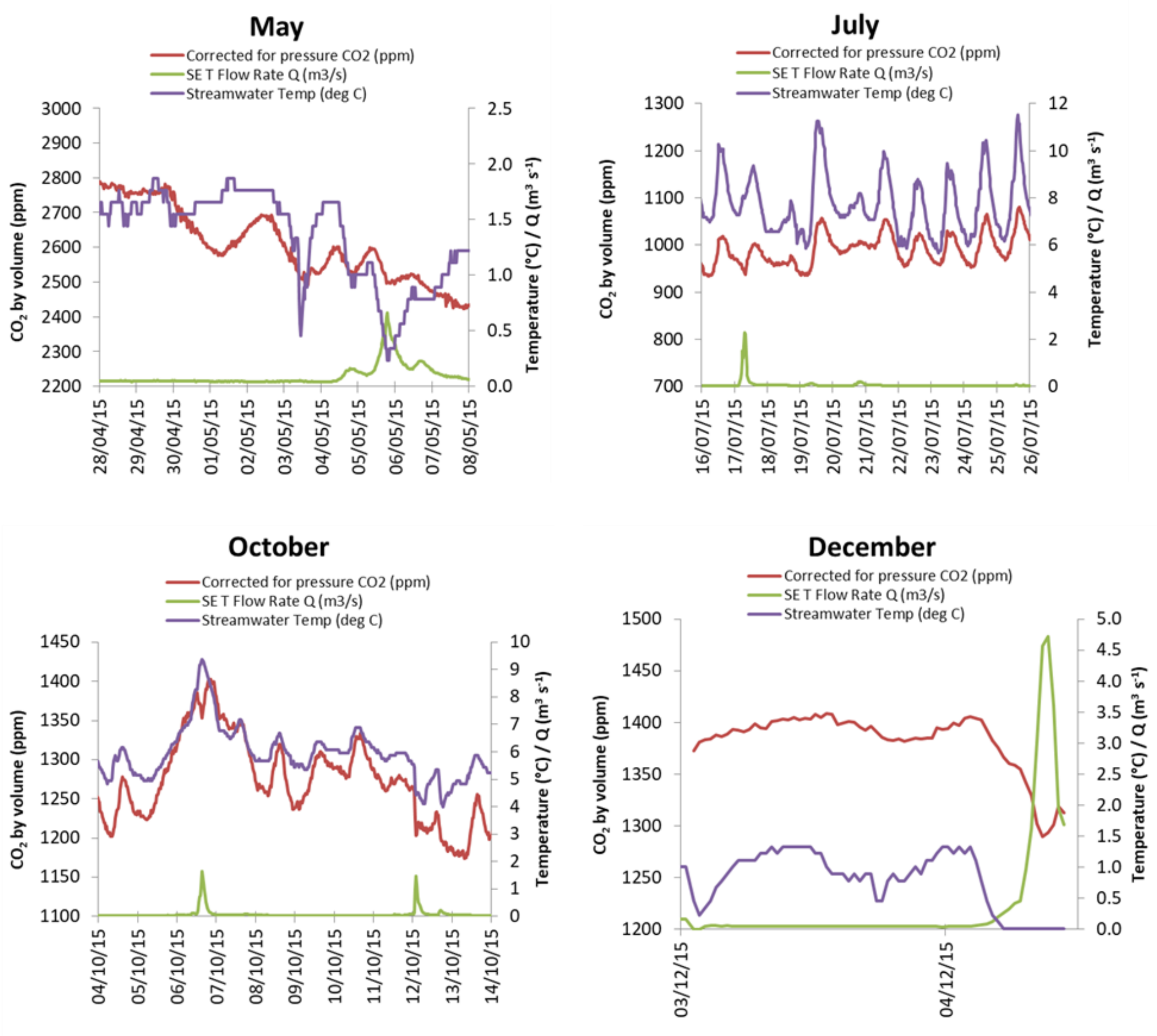


Figure 5-37: Seasonal changes in dissolved CO_2 at MM SE T

Time series plots of dissolved CO_2 concentrations, stream temperature and flow rate for different months illustrate responses to temperature changes and flow peaks.

The plots shown above for short periods through the year illustrate how concentrations of dissolved CO_2 respond to a diurnal cycle (effect of solar radiation and temperature changes) and also to high rates of flow (in response to rainfall events). Note that the plot for December is only for a short duration due to loss of the instrument. The seasonal responses can be characterised as follows:

- Spring (May) shows only a slight diurnal response with the CO_2 concentration increasing as temperature increases during daylight and decreasing with falling temperature at night. Water temperature is low as there is still some snowpack present. Increases in flow rate temporarily lower CO_2 concentrations (as CO_2 rich groundwater is diluted) but concentrations increase again as flow rates fall. Overall CO_2

concentrations are high but decreasing during this period. The significance of the spring season was highlighted in a study in forested peat catchments in east Finland which found significant fluxes of all carbons species (DOC, POC, DIC, CO_2 and CH_4) occurred during the spring snowmelt. This accounted for 37-45 % of the annual flux being released in one season (Dyson *et al.*, 2011).

- Summer (July) shows a strong diurnal response with the water temperature and CO_2 concentrations increasing with daylight/solar radiation. Water temperatures are relatively high and CO_2 concentrations are low but increasing slowly. High flow events temporarily reduce the concentrations of CO_2. The relationship between flow and CO_2 concentration was not as consistent across five headwater streams monitored in Canada, Scotland, England, Sweden and Finland. It found variability in lag times amongst the monitored streams in peak CO_2 response from 20 minutes before peak flow to two days following the peak flow (Dinsmore *et al.*, 2013).

- Autumn (October) shows a strong diurnal response with the water temperature and CO_2 concentrations increasing with daylight/solar radiation. Water temperatures remain relatively high and CO_2 concentrations are moderately high but decreasing slowly. High flow events temporarily reduce the concentrations of CO_2.

- Winter (December) shows a weak diurnal response with the water temperature and CO_2 concentrations increasing only slightly with daylight. Water temperatures are low and CO_2 concentrations are moderately high and increasing slowly. High flow events temporarily reduce the concentrations of CO_2.

It is clear from the data that dissolved CO_2 concentrations fluctuate based on diurnal changes in water temperature/solar radiation. As temperatures increase with daylight CO_2 concentrations increase and, inversely, fall through the night with lowering temperatures. The proportion of dissolved CO_2 in streamwater is known to vary with pH and temperature according to the carbonate buffering system (Hope *et al.*, 1995; Garnett *et al.*, 2012). Response to high flow events show concentrations of dissolved CO_2 falling on the rising limb of the hydrograph and increasing again as flow decreases. This would indicate that the baseflow of the stream has a much higher dissolved CO_2 concentrations than the runoff during the rising limb of a storm hydrograph which will predominately consist of direct rainfall and surface runoff which might be expected to have less direct contact with peat and more opportunity to degas to the atmosphere. As flow decreases, the CO_2 concentrations build again as a greater proportion of stream water comes from CO_2 enriched groundwater. The seasonal pattern DIC (increasing sharply through winter to peak in April before falling off rapidly between April and June) appears to correspond to the presence of snowpack and may be connected to the effects of ice on groundwater retention time and pathways. Groundwater will become more enriched with CO_2 if it is retained for longer periods of time or flows through deeper or longer pathways before reaching the stream. A study of age and source of dissolved CO_2 concentrations in a headwater peatland stream in Central Scotland had the lowest rates occur in the winter and highest rates occur during the summer (Garnett *et al.*, 2012). Streamwater CO_2 concentrations were highest during lower stream flows as deeper layers of the peat profile contribute more gaseous carbon (Dinsmore and Billett, 2008; Garnett *et al.*, 2012).

5.9.1 Calculation of DIC carbon export

Dissolved CO_2 concentrations recorded in 2015 at the Mòine Mhór south east tributary by the Vaisala Carbocap NDIR sensor can be used, along with calculated flow rates and runoff values, to calculate annual carbon loss from the Mòine Mhór area. Although incomplete the data set gathered in 2015 is large enough to make a good estimation of annual carbon loss from DIC (CO_2).

The Vaisala Carbocap NDIR sensor measures CO_2 concentrations in ppm by volume (or mole) in air. In order to estimate weight of carbon loss this needs to be converted to mg/l or mg/ m^3. The conversion of ppm to mg/m^3 of CO_2 in air takes into account the molecular weight of CO_2 (44.01 g/mol) which is considerably different from the average molecular weight of air (approx. 29 g/mol).

Mean SE Trib stream dissolved CO_2 concentration for 2015 dataset= 1302.529 ppm;
*This converts to 2345 mg/m^3 or 2.35 g/ m^3 = 1302.529 * 0.0409 * 44.01;*
Mean rate of flow MM SE Trib for 2015 = 0.085 m^3/s and
This gives an annual discharge of 2,680,560 m^3 and 6286 kg of DIC CO_2, converted to DIC CO_2-C by multiplying by 12/44 =1714 kg.

Equation 5-3: Annual discharge of DIC CO_2

This DIC export can be more meaningfully expressed when related to the catchment area as grams of carbon per square metre in a year (g C m^{-2} yr^{-1}). The Mòine Mhór south east tributary catchment area is 1.14 km^2. DIC export from CO_2 for 2015 as measured in the Mòine Mhór south east tributary catchment area is 5.93 g C m^{-2} yr^{-1}. This DIC export figure has been calculated for CO_2 concentrations only (as measured by the Vaisala Carbocap NDIR sensor). The dataset for 2015 from the NDIR sensor was incomplete but large enough to be a reliable indicator of annual figures as DIC data was collected on 208 days of the year in 2015 (57 % complete).

5.10 Erosion of stream banks

An estimate of erosion volume from each of the catchments was made by carrying out a stream peat block survey in 2015 (30th September) and this was then repeated a year later in 2016 (30th September) to compare results (Table 5-18). A block was classified as a loose clump of peat on the surface of the ground that could be transported by either rain or wind into the stream. This small study was carried out to try and estimate the volume of loose peat that could be transported into the stream channel and thus contribute to the organic carbon budget of the study site. The quantification was in a manner that made use of available resources and time.

Table 5-18: Replicated peat block survey results for 2015 and 2016

The area surveyed was calculated by the length of bank (variable from 50 m to 250 m) walked multiplied by the width (5 m) from the stream observed for peat blocks. A near and far bank was surveyed to give a total survey width of 10 m. The length, width and depth of the peat block were measured in the field and were then used to calculate the volume of the block.

Survey Location	Number of Blocks		Area Surveyed (m^2)	Volume of Blocks (cm^3)		Mean Size of a Block (cm^3)	
	2015	2016		2015	2016	2015	2016
Eidart U	5	93	1500	563	7786	113	84
CD U	0	13	2500	0	9874	0	760
CD NE	3	15	2500	12375	662	4125	44
CD NW	22	24	500	95961	3438	4362	143
CD L	50	22	1000	50037	17370	1001	790
Gar E	0	1	500	0	25	0	25
Gar NE	0	0	500	0	0	0	0
MM SE T	0	0	500	0	0	0	0

The mean sizes of the peat blocks in 2015 were always larger than those identified in 2016 unless there were no blocks identified during the survey of 2015. In 2015, a lot of erodible loose peat material was capable of transportation from the Caochan Dubh catchment (Caochan Dubh north east, Caochan Dubh north west and Caochan Dubh lower). No blocks were found at Garbhlach east during 2015 and only one block was identified during 2016 probably because this catchment had good vegetative cover. No blocks were found at Garbhlach north east or the Mòine Mhór south east tributary during 2015 and 2016. These streams are smaller in size than the Caochan Dubh lower and Eidart upper so the lesser flows may have reduced the potential for formation of blocks on the bank side. A larger survey area may have increased the chance of finding blocks at the Mòine Mhór south east tributary. The Garbhlach north east catchment is located within a steeply sloping valley. Therefore, any blocks could be washed away quickly, which may account for why no blocks were identified during the survey of 2015 and 2016.

As rainfall can act as a transport mechanisms the weather conditions were noted during the times surrounding the survey. The weather on the first sampling date (30th September 2015) was dry leading up to and on the day of the survey. The only precipitation recorded at the Ridge AWS and Meur Shuas TBR was on the morning of the 26th September 2015 (0.4 and 0.6 mm respectively). The weather for the second sampling date (30th September 2016) was dry on the day of the survey but wet on the days leading up to it. Data from the Ridge AWS showed that a total of 1.2 mm, 7 mm and 4.6 mm fell on the 27th, 28th and 29th September 2016 respectively. These values are confirmed by the Meur Shuas TBR where 1.7 mm, 9.6 mm and 5 mm of precipitation was recorded on the 27th, 28th and 29th September 2016 respectively. This may have had an influence on the amount of loose material on the river banks on the chosen survey dates as rain acts as a transport mechanism for peat material.

Another survey undertaken to attempt to quantify erosion on the study site was the astro turf mat and bucket study for which methods were previously outlined in Section 4.13 but this unfortunately did not return any successful results. A summary of the survey results logged and evidence of any material captured is presented in Table 5-19.

Table 5-19: Summary of astro turf mats and bucket survey

Date	Observation
01/09/2015	Deployed astro turfs at Eidart U, Caochan Dubh, Caochan Dubh Lower, Gabhlach East and MM SE trib. Deployed buckets at Eidart upper, Caochan Dubh, MM SE trib.
09/09/2015	One dried out fleck of peat in Eidart U bucket.  All other buckets and mats were empty / clean.
03/06/2016	Caochan Dubh bucket has some water sitting within it and a small trace of peat material present.  All other buckets and mats were empty / clean.
04/08/2016	Gabhlach East astro turf mat had sediment and peat on it. Believe stream had come out of banks and covered it, estimated 10 % coverage:  Mesh had been ripped off Eidart upper bucket, nothing in it. Eidart U astro turf had ~2 % coverage, most peat around edges: 
30/09/2016	Removed all buckets and astro turf mats from site.

No material captured within the buckets or astro turf mats was removed from the study site as had been planned originally to determine its volume and weight. Some material was evident within the buckets and stuck in between the mats however it was of an insignificant volume to remove, it was also difficult to extract the material from the sticky astro turf surface. Over the duration of deployment some interesting observations were noted. Within 10 m of stream channels in the Cairngorms alluvial soils dominate the riparian areas (Gibbins *et al.*, 2001). One of the mats was placed within 10 m of the Garbhlach east stream and alluvial fine grained sediment was deposited by overbank river flows onto the stream bank as discovered on a study site visit on the 4th August 2016 (see Figure 5-38). It was believed that the sediment was water borne due to the visible trash line from the stream. An estimate of 10 % coverage (containing a mix of sand and peat) of the mat area was estimated.

Figure 5-38: Astro turf mat as discovered on 4th August 2016

Note the darker clumps of peat visible trapped amongst the astro turf. Other water borne material deposited upon the river bank was also visible.

It is believed that peat material was mobilised around the site however the mechanism to quantify this movement through use of asrto turf and buckets was unfortunately not particularly successful. It is predicted that material may have ended up entering the buckets however if it did, it may have been blown out or washed away before collection and therefore not resulting in any worthwhile quantification. Removing the material from the sticky surface of the astro turf mat was also not practical. It was concluded from the astro turf and bucket study that the main processes eroding the peat appeared to be aeolian processes and the erosive force of moving water resulting from either from rainfall or snowmelt. Where an area of eroded peat already existed, this area tended to grow outwards with channels of water carving its way through the bare peat areas. Trampling over these bare peat areas also mobilised some loose material. Eroded material was observed to move by a combination of these transport mechanisms.

The area of bare peat without vegetative cover is susceptible to shrinkage, forming cracks, pipes and holes drying the peat out further, which can lead to gully formation. Shrinkage cracking of upland peat during dry summer periods

(Holden and Burt, 2002a; c; Holden, 2005b) is accentuated by the higher precipitation totals alongside impeded drainage with large changes in hydraulic conductivity over short vertical and lateral distances (Holden and Burt, 2003b). The erosive forces of freezing and thawing together with summer drying of the peat cause the surface removal of peat (Figure 5-39). This mobile surface is not favourable for vegetation re-establishment therefore human intervention may be needed to allow a blanket bog moss layer to be established. That and a palatable taste from grazing animals for young cottongrass, flowering heads of grasses and sages lead to the removal of sources of new vegetative growth (Moors for the Future Partnership, 2012).

Figure 5-39: Bare peat cracking during the summer months on the Mòine Mhór

Photographs were taken in Coire Garbhlach catchment when walking from Gar NW site to Caochan Dubh at approx. 289252, 794740. Desiccation (state of extreme dryness) cracking is a major initiator of pipes networks and climate change may increase the presence and density of pipes in blanket peat (Jones, 2004). Photograph from the 3rd of June 2016.

The Mòine Mhór streams had comparable catchment characteristics with a peat block study at the Trout Beck stream, North Pennines which concluded that peat blocks formed a significant stream load component and had an influence on sedimentation (Evans and Warburton, 2001). Very few of the blocks encountered at the Mòine Mhór were of sufficient size to be an obstacle within the channel and would instead be transported down the channel rather than forming a 'peat jam' or altering the flow dynamics of the stream. It is acknowledged that the larger blocks within the streams surveyed at the Mòine Mhór would have capacity to cause scour or become trapped within undercut channel banks or on channel bars. Some peat blocks of this size were recorded during the peat block survey and other obstacles which would alter the channel shape such as ice blocks were encountered throughout the project duration (Figure 5-40). Approximately 15 % of the Mòine Mhór is eroded, 17 % of the blanket peat is eroded at Trout Beck, and a block study on an upstream section of the channel at Trout Beck indicated that the channel ecosystem is a leaky system. This is typical of the headwater environment where organic matter is not retained efficiently (Crowe and Warburton, 2007).

a)
b)


Figure 5-40: Obstacles to flow within the headwater streams

Peat block in the channel resulting from bank collapse at the CD L site, photograph was taken on 30th September 2016 (a). Ice blocks within the channel, photograph taken on the 17th November 2015 with the spade placed in the centre of the channel where water would normally flow (b).

To summarise, the peat blocks that end up on the banks of the stream and within the channel highlight that this aspect is also an important source of organic matter from this upland catchment study site. The control of this aspect of carbon loss from the stream would be important to consider when looking at improving the carbon storage capacity of this site. Obstacles that have the capacity to restrict or alter the channel flow were found all year in the Mòine Mhór streams, such as the larger peat blocks identified during the autumnal months and the ice blocks observed in the channel in the winter months.

5.11 Aquatic carbon budget

5.11.1 DOC export from the study streams

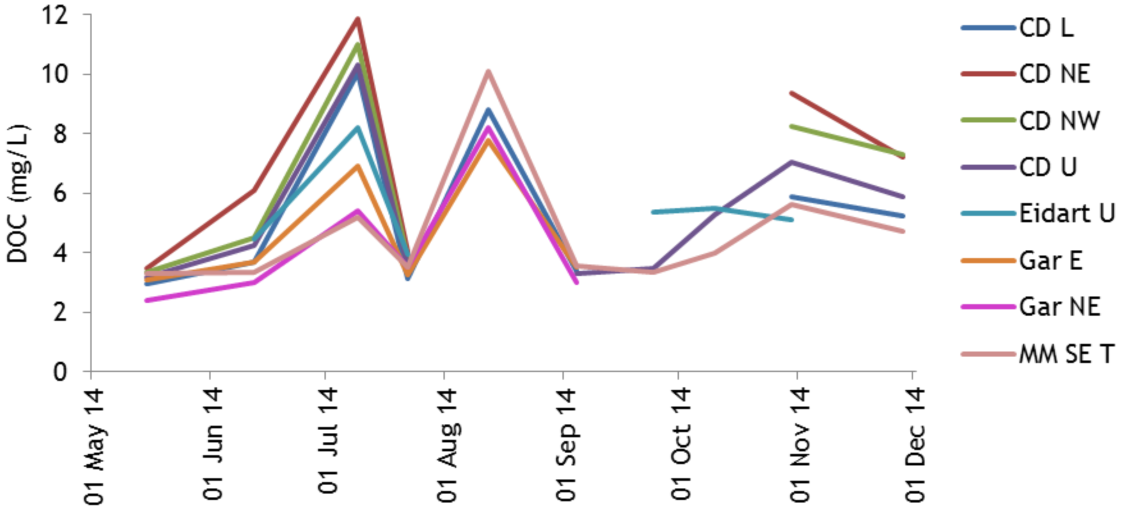
The process of the movement of water through peat prompts carbon storage and flux on a smaller site scale (Holden, 2005c). However, changes in carbon fluxes can have larger scale impacts when considering intensified terrestrial carbon release from this process happening in many peatlands across the world. The carbon loss can be considered irreversible in a human lifetime representing a challenge for managing the impacts of climate change and emissions. Given this, it is important to understand the peatland hydrology in order to further understand the balance and factors responsible for peatland development and decomposition (Holden, 2005d).

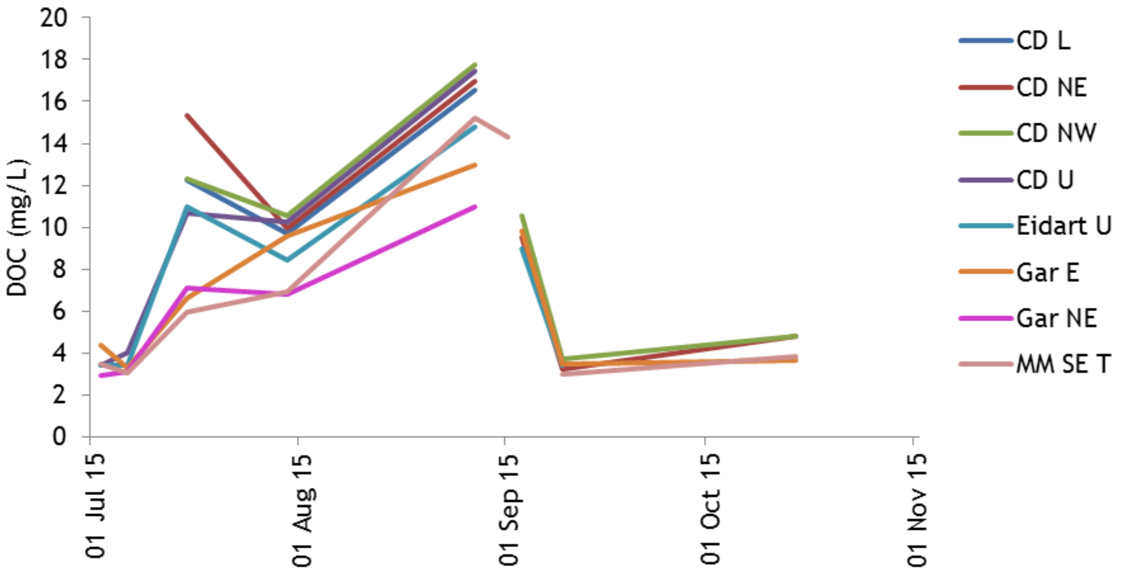
For the study, water samples were collected from the stream environment and it is acknowledged that producing a complete carbon budget is beyond the scope of what was undertaken during this project. However, the DOC results collected from the stream environment will help with building an understanding of the carbon budget and whether the peatland is storing more carbon than it is releasing. Among many other important factors outlined in the literature review, the concertation of DOC in the water can impact on stream productivity, biogeochemical cycles, attenuation of visible and UV radiation and water quality (Pastor *et al.*, 2003).

As DOC was only continuously monitored at one stream location, the Mòine Mhór south east tributary through use of the spectro::lyser, the water samples collected from the other streams were used to help estimate and make comparisons of DOC loss from the study area. The sample results will help to understand if catchment specific spatial variations exist. The laboratory measurements of absorbance (Section 5.6) allowed the DOC loss from the eight study streams draining the Mòine Mhór to be estimated. A strong linear correlation exists between absorbance at wavelength 254 nm and concentration of DOC (Dobb *et al.*, 1972; Mattson *et al.*, 1974; Brandstetter *et al.*, 1996; Deflandre and Gagné, 2001).

A linear regression was carried out on the Mòine Mhór south east tributary data on values that were available for wavelength measured at 254 nm in the laboratory and DOC concentrations measured from the LabTOC machine at CEH Edinburgh. It was hoped that a strong linear correlation would exist between absorbance and DOC but the reported r^2 value of 29 % displayed a weak relationship. This may have been attributable to the small number of observations as only sixteen samples were available to be included in the regression. For this reason, it was decided to use another regression equation for estimating DOC for the eight monitored catchments. The equation chosen ($DOC = 24.1 * Abs_{254} + 2.2$) achieved an r^2 value of 96 % (Smart *et al.*, 1976). This method of predicting DOC for the Mòine Mhór south east tributary reflected the measured DOC to +/- 0.19 mg/L which gave sufficient confidence in the use of this equation.

The predicted DOC concentrations for water samples in which absorbance was measured at 254 nm from the eight monitored catchments during May to December 2014 are shown in Figure 5-41. The Caochan Dubh tributaries (Caochan Dubh north east and Caochan Dubh north west) had the highest DOC concentrations followed by the upper and lower sites. The Eidart upper site had intermediate concentrations whilst the lowest concentrations occurred at Garbhlach east and Mòine Mhór south east tributary. The Garbhlach north east had the lowest predicted DOC concentrations in 2015. This correlates well with the finding of no peat blocks on the river banks of the Garbhlach north east site during the 2015/16 study (Table 5-18). The pattern of higher DOC from the Caochan Dubh and lower from the Mòine Mhór south east tributary and Garbhlach streams is again seen in the predicted DOC concentration during July to October 2015. In 2016, the Garbhlach east had notably lower predicted DOC concentrations when compared with the Caochan Dubh north west, and concentrations in the Eidart upper were again intermediate (Figure 5-41).


DOC (mg/L)
0
2
4
6
8
10
12
01 May 14
01 Jun 14
01 Jul 14
01 Aug 14
01 Sep 14
01 Oct 14
01 Nov 14
01 Dec 14
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T


DOC (mg/L)
0
2
4
6
8
10
12
14
16
18
20
01 Jul 15
01 Aug 15
01 Sep 15
01 Oct 15
01 Nov 15
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T

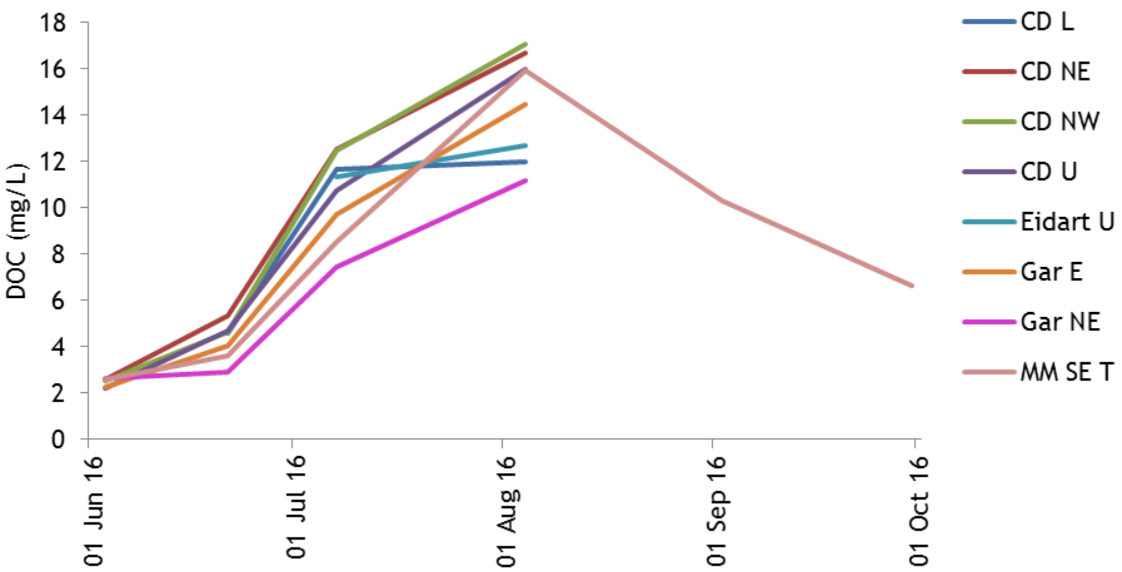

DOC (mg/L)
0
2
4
6
8
10
12
14
16
18
01 Jun 16
01 Jul 16
01 Aug 16
01 Sep 16
01 Oct 16
CD L
CD NE
CD NW
CD U
Eidart U
Gar E
Gar NE
MM SE T

Figure 5-41: Predicted DOC concentrations for 2014, 2015 and 2016

The DOC was predicted from the data collected at absorbance wavelength 254 nm given the known relationship (Edzwald *et al.,* 1985).

The mean predicted DOC concentration was calculated from where data was available for all eight catchments (10 dates) (Table 5-20). The mean predicted DOC ranged from 6.2 mg/L in the Garbhlach north east to 11.0 mg/L in the Caochan Dubh north east. The least eroded catchment, the Garbhlach north east (16 % bare peat) had the lowest mean DOC concentration whilst the three most eroded catchments, the Caochan Dubh north west, Caochan Dubh north east and Caochan Dubh upper (35, 38 and 42 % bare peat respectively) had the highest mean DOC concentrations. Export of DOC taking account of site specific flow conditions at the study catchments was then estimated.

Table 5-20: Mean predicted DOC concentrations for the monitored streams based on grab water samples

Stream	Mean predicted DOC (mg/L)
CD L	9.1
CD NE	11.0
CD NW	10.4
CD U	9.5
Eidart U	8.6
Gar E	7.9
Gar NE	6.2
MM SE T	7.5

To provide an estimate of the carbon export from the different streams draining the study site, the predicted DOC concentrations in the water samples were multiplied by the stream flow at the time of sample collection and then converted to a DOC flux in gC/m^2 as displayed in the calculations table presented in Appendix G. It is acknowledged that this is across a small dataset (10 sample dates where all streams were visited on the same day) covering from 2014 to 2016 but it does give an indication as to the differences or similarities in DOC export between the monitored streams. A summary of the maximum, minimum and standard deviation of the calculated DOC flux numbers is displayed in Table 5-21 below.

Table 5-21: Summary of the maximum and minimum DOC flux from the study streams

The calculation used to derive these values is displayed in Appendix G. The samples cover 10 dates inclusive of the period from June 2014 through to September 2016. The percentage of bare peat per catchment area is taken from Figure 3-7.

Stream	Max DOC Flux (gC/m^2)	Min DOC Flux (gC/m^2)	Mean DOC Flux (gC/m^2)	Standard Deviation	Bare peat (%)
CD L	4.9	0.15	1.1	± 1.4	34
CD NE	1.0	0.18	0.5	± 0.3	38
CD NW	1.2	0.20	0.5	± 0.3	35
CD U	2.7	0.19	1.0	± 0.8	42
Eidart U	12.0	0.30	2.8	± 3.6	27
Gar E	6.6	0.09	1.7	± 2.0	26
Gar NE	3.1	0.08	1.3	± 1.1	16
MM SE T	19.5	0.15	2.7	± 6.3	30

The minimum and maximum values display the range captured from 0.08 gC/m^2 (Garbhlach north east) through to 19.5 gC/m^2 (Mòine Mhór south east tributary). The DOC flux during the comparable seasonal month of August at Cottage Hill Sike, a blanket peatland catchment of 0.074 km^2, 98 % blanket peat coverage, located in the north of England was 1.76 gC/m^2 (Grayson and Holden, 2016). Due to the small number of values, they have not been summed to give a monthly total however the mean values of 0.5 to 2.8 gC/m^2 are comparable to those reported in the Grayson and Holden study.

When sorted by maximum through to minimum DOC flux or from highest mean to lowest mean DOC flux, there was no clear relationship between catchment DOC flux and percentage of bare peat. Although the streams were visited on the same day, a variety of flow conditions were captured which may have been impacted on the results observed. No clear trend can be drawn from these results, although the Caochan Dubh streams (Caochan Dubh north east, Caochan Dubh north west and Caochan Dubh upper) had the lowest mean and maximum DOC fluxes. In order to make comparisons with other studies, an annual DOC flux was calculated from the one continuously monitored stream, the Mòine Mhór south east tributary.

5.11.2 DOC loss from the MM SE T

From the spectro::lyser data collected (Section 5.7) an estimate of the annual loss of carbon from the Mòine Mhór south east tributary catchment can be estimated. This was made using the flow and concentration data collected from June 2014 to September 2016. The flow and DOC concentrations were multiplied together and then converted to g of C per m^2 by dividing the DOC (in grams) by the Mòine Mhór south east tributary catchment area (in m^2) to give a value in gC/m^2 for each individual sample time point. The flux values were then summed and split into the individual study years. Next the fluxes for each year were scaled to an annual value, taking account of the number of measured days the $gC/m^2/yr$ was calculated by dividing the annual loss by the catchment area as indicated in Appendix G, with results displayed in Table 5-22. The DOC exports for the Mòine Mhór south east tributary were estimated utilising the 15-minute DOC spectro::lyser concentrations and the 15-minute calculated flow values. For comparison, the DOC export was also calculated for the Mòine Mhór south east tributary using modelled flows which are presented as hourly flow values so hence the spectro::lyser DOC values expressed as an hourly mean were utilised for these concentrations. The 15-minute and hourly interval data have been taken account of in the scaled up exports calculated (Table 5-22).

Table 5-22: DOC export from the MM SE T

The 2014 study year starts on the 2nd June 2014 as this is when the spectro::lyser was deployed. The 2016 study year ends on the 30th September 2016 as this is when the study year ends and when the equipment was removed from the site. The numbers provided for the MM SE T measured flows are based on 15-minute flow data and 15-minute DOC data. The gC/m^2 per year is the sum of the available 15-minute values. The numbers provided for the MM SE T modelled flows are based on hourly flow data and hourly mean DOC data, further information of the derivation of this dataset was provided in Section 5.4. The gC/m^2 per year is the sum of the available hourly values. From both calculations the completeness of data may be impacted by instrument reliability or as a result of the removal of suspect and spurious data values. During the winter months the spectro::lyser dataset was also reduced from 15-minute logging to hourly logging to conserve battery power. Only where both a flow value and a DOC value are available have the values been included in the calculations.

Stream and flows	Year	Completeness (%)	Scaled up to 365 days, sum of DOC export ($gC/m^2/yr$)	Standard Error
MMM SE T measured flows	2014*	54	9.73	0.01
	2015	51	28.1	0.01
	2016”	44	22.2	0.01
MMM SE T modelled flows	2014*	50	4.33	0.02
	2015	84	6.32	0.01
	2016”	74	5.46	0.01

*From the 2nd June 2014 to 31st December 2014
“From the 1st January 2016 to 30th September 2016.

The difference in the flow values between the measured and the modelled flows might contribute for some of the differences observed in the calculated export values. The range of DOC export values from the measured flows ranges from 9.7 to 28 $gC/m^2/yr$ whereas values calculated from the modelled flows ranged from 4.3 to 6.3 $gC/m^2/yr$. These values are of similar magnitude with those reported in the literature with the Moor House, an upland peat catchment in

North Pennines with a catchment area of 11.4 km^2 estimated as having an annual flux of DOC of 9.4 to 15 $gC/m^2/yr$ (Worrall *et al.*, 2003a). For comparison, DOC annual fluxes from two contrasting acidic catchments in Mid-Wales and the north east of Scotland were 8.4 and 17 $gC/m^2/yr$ respectively (Dawson *et al.*, 2002).

The majority of the DOC is transported during storm (rainfall) events in peatlands (Clark *et al.*, 2007; Labadz *et al.*, 2010). The DOC export per year at the Mòine Mhór SE T catchment area was estimated by multiplying the upper value of 28 $gC/m^2/yr$ by catchment area (1140000 m^2) then dividing by 1000 to convert the value to kgC/yr. This gave 31,920 kgC/yr of annual DOC loss from the Mòine Mhór south east tributary catchment, equating to a total carbon loss through runoff of 31 tonnes of C yr.

5.11.3 Erosion block study

In relation to the results from the peat block erosion study (Section 4.13), the volume of loose material that had the potential to be deposited into the streams on the Mòine Mhór catchment was calculated (Table 5-23). This was determined by multiplying the loose peat per sample area calculated for the monitored streams in 2015 and 2016 by the area of the river bank within the catchment. This gave an approximate volume of loose peat blocks on the stream banks scaled up to all the streams draining the study site.

Table 5-23: Calculation of the amount of loose material on the river banks of the Mòine Mhór in 2015 and 2016

Area of river bank surveyed (m^2) was calculated by multiplying the length of the river bank within the catchment area (boundary map shown in Figure 4-4) by the surveyed bank width (10 m). The loose peat per area sampled (cm^3/m^2) was calculated by dividing the volume of blocks by the area surveyed (values used available in Section 4.13). The estimated loose peat in river bank area (cm^3) was calculated by multiplying the loose peat per area sampled with the area of river bank.

Survey Location	Area of river bank (m^2)	Loose peat per area sampled (cm^3/m^2)		Estimated loose peat in river bank area (cm^3)	
		2015	2016	2015	2016
Eidart U	18000	0.38	5.19	6840	93420
CD U	18000	0	3.95	0	7110
CD NE	6150	4.95	0.26	30443	1599
CD NW	6500	191.92	6.88	1247480	44720
CD L	7000	50.04	17.37	350280	121590
Gar E	12000	0	0.05	0	600
Gar NE	4500	0	0	0	0
MM SE T	12500	0	0	0	0

The estimated loose peat from each of the surveyed streams was then summed and converted from cm^3 to m^3. This gave an approximate amount of loose material on the stream banks on the Mòine Mhór for the surveyed years of 2015 and 2016. For 2015 this value was 1.63 m^3 and for 2016 it was 0.33 m^3. Loose peat has the potential to contribute to the aquatic carbon budget by being washed off into the stream thus negatively impacting on water quality, carbon storage and the emission of greenhouse gases. For comparison, 38.3 m^3 of in-channel peat blocks were recorded at a reach of the Trout Beck, North Pennines, in July 1998, with 8.5 m^3 estimated to have been contributed to the stream from local bank collapse (Evans and Warburton, 2001). The Trout Beck study involved surveying 100 m reach recording blocks present in channel and on the floodplain. The blocks were observed to cluster on bars and settle on gravel bars.

In summary, the prediction of DOC using the water samples collected from the streams was useful to see if exports varied between the catchments. It was found that the least eroded catchment, the Garbhlach east, had the lowest mean DOC (6.2 mg/L) whereas the more eroded Caochan Dubh catchments had higher mean DOC concentrations (9 – 11 mg/L) for spot flow measurements and samples. When flow was taken into account and the mean DOC fluxes were calculated, the mean DOC flux ranged from 0.5 gC/m^2 (Caochan Dubh north east and Caochan Dubh north west) to 2.8 gC/m^2 (Eidart upper) which have the smallest and largest catchment areas respectively. Using the spectro::lyser dataset and the measured and modelled flows, annual DOC exports were calculated for the Mòine Mhór south east tributary catchment. The export values calculated using measured and modelled flow differed. This can be partially explained by the differences in methods used to derive the flows and the measured DOC concentrations based on 15-minute data whereas the modelled flows were based on hourly data. For the most compete year of 2015 the exports ranged from 6.3 $gC/m^2/yr$ using the modelled flows to 28 $gC/m^2/yr$ for the measured flows. The upper values are rather high for an export value and resulted in a calculated annual loss of 31 tonnes of carbon per year. The erosion block study showed that measuring the in-channel material and bankside material can improve the accuracy of quantifying the complete aqueous budget. The stabilisation of the bank material is important for minimising the material lost in this way. More loose peat was recorded in 2015 (1.63 m^3) compared to

2016 (0.33 m^3). This may have been attributable to the higher rainfall on the days prior to the 2015 survey being undertaken resulting in the mobilisation of a greater volume of material.

5.12 Results summary

The River Feshie is relatively flashy with runoff varying from 801 mm in 2012/13 to 1308 mm in 2014/15. Runoff was overestimated in the study catchments however this was also found in the modelled flows. With reference to the water chemistry results, patterns of seasonal and inter-annual variability were present for absorbance, pH and conductivity. Maxima generally occurred in the spring and summer months. The maximum water chemistry parameter response tended to occur on the day of or the day after the highest flows were recorded. In addition to the streamwater TOC and DOC results presented, of other interest to the aquatic carbon budget are the streamwater DIC concentrations and the results of the peat block survey.

In summary, the DIC export for the Mòine Mhór south east tributary was calculated as 5.93 $gC/m^2/yr$. The DOC fluxes ranged from 0.5 gC/m^2 (Caochan Dubh north east and Caochan Dubh north west) to 2.8 gC/m^2 highlighting that the smaller catchments are exporting less carbon. The standard deviation in DOC flux was greatest for the Mòine Mhór south east tributary indicating a greater range in response from this stream when compared to the others. The spectro::lyser dataset allowed annual DOC exports to be calculated for the Mòine Mhór south east tributary. These ranged from 9.73 to 28.1 $gC/m^2/yr$ when calculated using measured flows. The peat block survey found higher amounts of loose peat per sample area on the Eidart upper, Caochan Dubh lower and Caochan Dubh north west tributary streams indicating the potential higher POC exports from these streams in relation to the others. There was no consistent relationship between catchment characteristics and the peat volumes and DOC export estimates. This indicted the difficultly in predicting catchment exports from catchment characteristics.

6. Discussion

6.1 Summary of findings

The overall aim of this research was to assess the aquatic carbon fluxes and monitor the spatial variability of peatland extent, condition and water chemistry within and between the Glenfeshie Mòine Mhór catchments. This would be helpful for producing a detailed study of streams draining a high altitude eroded peatland site in Scotland (Section 1.4) and contribute to the field of ecohydrology and management (Section 1.3). The main findings of the research with reference to the project objectives are discussed in more detail below.

6.1.1 Condition of the peatland and streamflow

From the seven streams monitored that drained from the study site, it was found that the Caochan Dubh lower had the greatest range of flows, followed by the Eidart upper, two of the largest river catchments. The lowest flow rates occurred in the Garbhlach north east and the smallest catchment of the Caochan Dubh north west (Table 5-8). The Caochan Dubh lower and Garbhlach north east catchments had the steepest slopes of the study catchments (Table 4-1). The bedrock geology of Dalradian schist occurs uniformly throughout the study area. The Garbhlach north east had the lowest bare peat areas (16 %) and flow rates compared to the other catchments. However, based on the other sites, it cannot be ascertained that the most eroded catchment had the flashiest flow regime or that the least eroded had more stable flows. With reference to the peat block study of the particulate material present on the river banks, it was found that the Garbhlach east had no blocks in 2015 and only one block was encountered in 2016 (Table 5-18). The Garbhlach east represented the second least eroded site after the steeply sloping catchment area of the Garbhlach north east and indicated that the findings of the peat block study linked well with the overall peat coverage within the study catchments.

In south-eastern Brazil, river flow patterns were studied in an eroded catchment and a catchment with similar physical characteristics but no erosion (Costa and Bacellar, 2007). The study concluded that the gully features in the eroded catchment resulted in a reduction in baseflow but an increase in the magnitude of the stormflow peaks. The variability in the erosion features between the catchments monitored on the Mòine Mhór was smaller so the clear-cut impacts of these features on the flow patterns is not as apparent. However, the numerous benefits, environmental, conservation and economical, that are associated with a well vegetated, good condition upland peatland headwater catchment are well established (Worrall *et al.*, 2011b; Qassim *et al.*, 2014; International Union for Conservation of Nature, 2018). The vegetation cover can help to intercept runoff and reduce the amount of peat material mobilised into rivers which is important for this study site.

Ecological recovery of the land is indicated by the native tree regeneration present in the lower glen (Figure 3-11). A major limiting factor for regeneration is the deer which graze and trample newly forming vegetation. However, within Glen Feshie, deer densities have reduced from an estimated 40 deer per km^2 in 2006 to 1.2 deer per km^2 in 2009 based upon dung counting, vegetation monitoring and direct counting with specific relevance to the study site and regeneration area (Thomas MacDonell personal communication in Evans (2012)). These numbers are still maintained to date through culling. During the study, it was observed from visual monitoring and through the presence of a camera that the deer would congregate in wet bare peat and peat hags within the Caochan Dubh catchment during the summer months. This may be because the erosional features naturally create a more hidden space for the deer to move and pass through. An observation of feeding behaviour was that the deer graze on new shoots of cotton grass growing on areas of bare peat (Thomas MacDonell, personal communication). This hinders re-colonisation of new flora on bare peat as herbivores may graze the vegetation before it has had a chance to establish. Given the preference of the deer to browse new vegetative growth and make use of the erosion features, it is suggested that deer may need to be excluded from an area to allow for regeneration of the peatland habitat. If not excluded, when deciding on the restoration methods, consideration should be given to the observed deer behaviour in how they currently use the eroded sections of the study site.

The impacts of deer on trampling, grazing and browsing are well studied (Baines *et al.*, 1994; Putman *et al.*, 2005; Pellerin *et al.*, 2006; Albon *et al.*, 2007). However, studies that track the behaviour and movement of deer through bare peat/erosional areas would also be of interest. When searching the literature to compare the field observation of how the deer use the bare peat areas of the study site, few papers were found on this topic area.

In relation to deer movement across the study catchments, higher deer numbers were noted at the Caochan Dubh catchment (centre of the study site) in comparison to the Eidart catchment (northern edge of the study site) although their presence was noted during fieldwork activities across the entire study site (Table 3-5). The wildlife camera was placed for a total duration of 8 months at the Eidart and at the Caochan Dubh (dates and locations in Table 3-4 and images in Figure 3-17) capturing 0 and 12 images respectively, indicating a preference for movement across the centre of the study site. It is well recognised that there is spatial and seasonal variability in deer movements and ranges as has been observed at this site (Scottish Natural Heritage, 2016a).

In conclusion, as expected, higher flows are produced from the largest of the catchments, with flow regimes being driven primarily by catchment size. It could not be concluded that the most eroded catchment had the flashiest flow regimes or that the least eroded site had the most stable flows. There were however spatial differences observed in how the deer use the site with a preference to move across the centre of the plateau. The browsing of deer on any potential revegetating areas of bare peat will require consideration when moving forward with the restoration of the area.

6.1.2 Seasonality

In relation to seasonal variations, the annual hydrological regime of the Mòine Mhór was found to be driven by considerable snow accumulations that can result in snow melt events in late winter, spring and summer. Snowmelt can release stored water that has the potential to cause the high peaks observed from the Mòine Mhór study streams. The highest daily flows were experienced during the spring (April, May) and winter months (November, December, March) at the study sites (Table 5-8). Patterns of precipitation through the year, characterised by complexity in space and time, determine the patterns of flow from headwater streams and how they combine to make up the flows of larger river systems (Soulsby *et al.*, 2002). It is also recognised that during freezing conditions winter baseflow can dominate and during the summer there is also the potential for storm events to occur in response to high rainfall. All these characteristic variations were seen from the monitored study sites whilst recognising that there is complexity in the flow pathways. The contribution from groundwater flows is unknown from the study site. However, it was reported to account for as much as 50 % of the annual runoff in the Allt a' Mharcaidh catchment, in close proximity to the Mòine Mhór (Soulsby *et al.*, 2002).

The surface temperature must warm above 0 °C for the snow and ice at the ground surface to begin melting. The warmer mean air temperature recorded in May 2016 (5.90 °C) would have melted the snow at a faster rate in comparison to the previous year when the mean air temperature was 2.09 °C in May 2015. Photographs in Figure 6-1 show the variability in snow melt rate between 2015 and 2016. This highlights that the Cairngorm climate is variable in terms of temperatures changes, resulting in snowpack accumulation and thawing, both of which can impact on stream flow and water quality (Soulsby *et al.*, 1997).

In terms of seasonal variability in the composition of streamwater samples collected, peaks in suspended sediment predominately occurred in winter and spring. Generally, maximum suspended sediment concentrations were recorded in response to high flow events which occur all year round, also observed by Grieve and Gilvear (2008). With absorbance, peaks occurred in the summer and are attributed to water often being locked up in snowpacks during the winter to spring months (Figure 5-24). This pattern of higher absorbance values in the summer and lower in the winter was also observed over a five year study at Malham Tarn Moss in North Yorkshire (Proctor, 2003).

Figure 6-1: Snowmelt variability between May 2015 and May 2016

The photo on the left was taken on 14th May 2015 and shows the snowpack melting across the study site. The photo on the right shows the snow almost completely gone at the same site on 19th May 2016. Snow still remained on site in 2016 but to a lesser extent when compared with the previous year.

The relationship between snowmelt and flow hydrology is of interest and relevance to the characterisation of the study site. The physical mountainous upland location of the study site means that snowpack accumulation and snowmelt exert significant control on the hydrological regime (Dunn *et al.*, 2001; Kay, 2016). Snow is sensitive to climatological variables which will be of relevance in a changing climate. A study which involved the methodical collection of snow data from the Allt a' Mharcaidh catchment from 1989-1998 by Soulsby and Helliwell highlighted the spatial and temporal variability in snow attributable to the climate (Soulsby *et al.*, 1997; Helliwell *et al.*, 1998). The significance and variations all year round has been highlighted in the study streams.

6.1.3 Variability in streamwater quality

The climate, soil, underlying geology, land use and hydrology all interact to influence the water quality of Scotland's rivers. Stream water samples were collected between May 2014 and September 2016 on a number of occasions with variabilities or similarities in the results discussed below.

Although not statistically significant, the Garbhlach east, Garbhlach north east and Mòine Mhór south east tributary had overall lower absorbance values when compared to the other monitored catchments (Figure 5-23). The lowest mean value for absorbance at 400 nm was the Garbhlach north east site at 0.022 nm, whereas the Caochan Dubh streams (lower, north east and north west) had the highest mean values ranging from 0.040 to 0.043 nm. As can be seen in Figure 3-7, all the monitored streams are surrounded by areas of bare peat. However, the least eroded catchments were the Garbhlach east and Garbhlach north east, indicating a possible relationship of lower colour in the less eroded sections of the site. The mean absorbance at 400 nm and 254 nm across all sites respectively was 0.034 ± 0.002 nm and 0.183 ± 0.012 nm highlighting that the water was generally very clear. In comparison, the absorbance values measured at 400 nm from the Trout Beck catchment, North Pennines were typically 0.05 to 0.1 nm, with peaks of 0.15 nm recorded (Worrall *et al.*, 2006). At the Cottage Hill Sike, an upland headwater tributary to the Trout Beck, the absorbance values typically ranged from 0.03 to 0.15 nm (Worrall *et al.*, 2006). The Trout Beck catchment is located on a blanket peat catchment at 500 to 848 m AOD that is in an eroded state due to the impact of drainage.

Similar patterns as for absorbance were also evident for turbidity across the study catchments. Turbidity was generally higher into Caochan Dubh north west and Caochan Dubh north east catchments and lower in the Garbhlach north east and Garbhlach east catchments with intermediate values at the Eidart upper site. Overall, the results for the monitored water quality were similar across catchments with no one particular stream or parameter standing out on every occasion.

The Eidart upper had a higher streamwater pH mean (7.11) compared with the more acidic Garbhlach north east, Caochan Dubh upper and Caochan Dubh north west catchments (mean pH 6.74 - 6.75). The pH of Scottish rivers is generally between 5 and 6 (Soulsby *et al.*, 2002) therefore the mean pH of the streams on the Mòine Mhór is higher than the upper expected range. The mean pH is slightly higher than the typical range which could be due to the limited vegetation and shallow soil and peat depths on the Mòine Mhór.

Water colour predominantly consists of DOC however there is no fixed relationship between these two variables as DOC can be more or less coloured in nature (Worrall *et al.*, 2007b). From the spectro::lyser data, a significant relationship was found between colour true and DOC (r^2 = 92 %, p value of <0.001) suggesting that DOC is one of the main causes of discolouration in the Mòine Mhór south east tributary stream. An important component of the peatland carbon budget is the quantification of the water borne flux of dissolved carbon. The fluxes of dissolved carbon are controlled by the hydrology of the peatland (directly and indirectly) (Waddington and Roulet, 1997).

In a study of a boreal stream system in northern Sweden it was found that the smallest catchments had some of the highest exports of DOC (Ågren *et al.*, 2007). For the Mòine Mhór streams this was not the case. There were variations in DOC between the catchments, but generally mean DOC fluxes were greatest from the larger catchments (Eidart upper, Mòine Mhór south east tributary) and lowest from the smallest catchments (Caochan Dubh north west and Caochan Dubh north east). Variations in DOC concentrations in upland/peatland UK catchments include both within annual cycles and over the longer term (Dawson *et al.*, 2008). Both high-frequency and long-term monitoring are important for understanding variations in DOC concentrations (Halliday *et al.*, 2012). For the lower mean annual precipitation catchments, such as those upland catchments in the east of Scotland, these typically have seasonal DOC concentration-discharge relationships with autumnal flushes of DOC (Dawson *et al.*, 2008). For higher mean annual precipitation catchments, the warmer temperatures from June to November increase biological activity and decomposition of available organic matter and solubility of DOC. Lower concentrations of DOC are experienced from December to May in these wetter catchments. The continuously monitored stream on the Mòine Mhór demonstrated that the seasonal patterns in DOC concentrations were typical of the higher precipitation catchments (Figure 5-27).

6.1.4 Storm events

The longer term dataset available for the River Feshie (1992-2016) showed that peak flows varied from 50-120 $m^3\ s^{-1}$ with events occurring across all seasons. The response time for the corresponding rise, peak and fall in the hydrographs based on daily data (Figure 5-4) was often 4 to 12 days, with the hydrological regime often driven by snowmelt. Further up the catchment in the headwater streams of the study site, the higher and wetter ground resulted in higher runoff values as a result of the increased precipitation. The Mòine Mhór streams had a much quicker response time, often in the scale of minutes to hours. Peaks in flow varied from 0.012 $m^3\ s^{-1}$ in the Caochan Dubh north west up to 10 $m^3\ s^{-1}$ in the Caochan Dubh lower. From the closest weather station (Ridge AWS, Figure 4-8) in terms of altitude and proximity (<2 km from the centre of the plateau) the response time between rainfall and rise in flow was often less than one hour.

On the Rough Sike channel reach in the North Pennines, a storm on 10th September 1998 had a peak discharge of 21 $m^3\ s^{-1}$ (Evans and Warburton, 2001). The channel width of 1.0 m and depth of 0.24 m is comparable with the Garbhlach north east catchment (Table 4-1). This one event moved the peat block material being recorded during the study downstream and resulted in fresh eroded peat material being added to the stream and becoming mobilised. During storm events the water can be out of bank as was encountered across the study period for the streams on the Mòine Mhór. This highlights the significance of one event in increasing the amount of material exported from the site.

Over 15 % of the site is covered by bare peat (Section 5.10). High annual runoff values (Section 5.3.6) and site observations confirm the presence of macropore flow and pipeflow within the Mòine Mhór streams. Thus, the Mòine Mhór is behaving like a drained area (Section 2.3.4.3). However, overland flow still represents a runoff pathway to the streams with water chemistry responding to precipitation events with a corresponding rise in water level (Section 5.8).

It is important for stream exports to be understood with reference to the hydrological pathways. Water which flows through surface organic soil horizons either surface, overland through flow or pipeflow and generally is more acidic, particularly during storm events due to the soil type and its low buffering capacity (Giusti and Neal, 1993). Overland flow, preferential flow and complex groundwater flow dominate during the summer and autumn which can influence the storm hydrograph response. The relationship between daily flow and water chemistry appeared erratic (section 5.6.3 and Appendix F). However there appeared to be a seasonal trend for pH, with summer peaks and winter minima, the range of difference equating to less than 1 pH unit (all streams within range of 6.58 to 7.25) (Section 5.6.2).

The Mòine Mhór streams behave like typical blanket peatland streams as demonstrated by the comparable short time of less than 24 hours to peak and recession in the storm hydrograph response (Burt, 1992; Evans *et al.*, 1999; Evans and Warburton, 2007). This may be attributed to the low water storage capacity of the site, where water tables are often close to the surface.

6.1.5 Aquatic carbon budget

With reference to the carbon budget of a peatland system, it is recognised that there are also the land-atmosphere fluxes which have not been considered here. These typically include eddy covariance measurements of net ecosystem exchange (Blodau, 2002; Ball *et al.*, 2007). The budget estimates in this study have focused on the aquatic system and exports of carbon downstream. Aquatic forms of carbon loss quantified include DOC, POC, and dissolved gas, including CO_2 which is a form of DIC. Although still important, as previously indicated (Section 2.6.6.3), the export of POC is generally less than DOC and represents a smaller part of the budget (Dinsmore *et al.*, 2010). Contributions from the weathering of silicate materials and the products of carbonate dissolution primarily make up the DIC input, which is one of the main controls on the pH of stream water (Hope *et al.*, 2004). DIC occurs in ionic forms as bicarbonate, carbonate ions, carbonic acid or as dissolved free CO_2 (Hope *et al.*, 1994).

Based on this study's results, an aquatic carbon budget from the eroded Mòine Mhór south east tributary study catchment is provided in Table 6-1 below. The DOC exports were calculated using the spectro::lyser dataset and flow gauging dataset from the Mòine Mhór south east tributary monitored stream (Section 5.11.2). The range of values presented is for the years 2014 to 2016 (Table 5-22). DIC export was calculated from the sensor which was also located in the

Mòine Mhór south east tributary during 2015 (Section 5.9). Since the Vaisala Carbocap did not capture a full year of data, there is some uncertainty associated with the values provided. It would also have been of value if more water samples could have been analysed by gas chromatography (GC) for dissolved CO_2 to aid in the sensor calibration. However, the estimated export does give an indication as to this part of the aquatic carbon budget.

The export of POC can be estimated using the TOC values collected from the spectro::lyser and flow gauging dataset from the Mòine Mhór south east tributary monitored stream. Given that TOC = DOC + POC (Figure 4-16) and based on the assumption that POC could represent anywhere from 30 to 50 % of the TOC (Fisher *et al.*, 1998), an estimate has been made. It is acknowledged that suspended sediment data could also be used to infer POC, however given the smaller dataset gained from this monitoring method, the TOC dataset has been utilised instead. It is noted that there is higher uncertainty with the POC value presented, given that it was not directly measured during the study period and is instead inferred as an estimated percentage from the TOC.

Table 6-1: Summary of aquatic carbon budget for the Mòine Mhór south east tributary study stream

The total presented in the bottom row of the table has been calculated from the mean values for DOC and POC.

Carbon species	Flux (gC/m^2/yr)	% of total
DOC	9.7-28 (mean = 20)	56
DIC	5.93 mean	17
POC	7.2-11.9 (mean = 9.6)	27
Total	**35.5**	**100**

Measurements at the Mòine Mhór south east tributary stream indicate that the mean carbon loss through DOC in aqueous runoff was 20 gC/m^2/yr. This can be compared to a measured mean loss of DIC of 5.9 gC/m^2/yr and a mean POC loss of 9.6 gC/m^2/yr. The contribution of the different carbon species to the budget is approximately a 50:20:30 for DOC, DIC and POC respectively.

In 2006 to 2007, 700 DIC samples were collected and analysed from 14 sub-catchments which drain into the Vindeln River located in northern Sweden (Wallin *et al.*, 2010). The 67 km^2 catchment area is typically snow covered from October through to May. The study site is at 130-369 m AOD with an annual precipitation of 600 mm. The highest DIC exports of 1.4 to 1.5 gC/m^2/yr were found from the headwater peatland streams. The DOC exports from these northern Swedish headwater peatland streams were 8.8 to 9.9 gC/m^2/yr (Ågren *et al.*, 2007). Factors that can influence these differences in export values relate to stream size, stream order, location, altitude, condition, gradient and flow pathways. The DIC exports summarised in Table 6-1 indicate that the Mòine Mhór streams have slightly higher values compared to the Vindeln River but are still within a comparable range for a similar site.

Flux estimates of DOC export ranged from 6.9 - 20.6 gC/m^2/yr from a study carried out on the Whitelee catchment after planning approval had been announced for a windfarm (Waldron *et al.*, 2009). These catchment losses are comparable with those reported in similar UK peat headwaters (Dawson and Smith, 2007). In this project, flux estimates of DOC export from the Mòine Mhór were 9.7-28 gC/m^2/yr based on 851 days of spectro::lyser data (02/06/2014 to 30/09/2016), which is aligned with these values and also represents a peat headwater catchment.

As demonstrated in other studies, inclusive of the Mòine Mhór, the DOC flux formed the highest component of the fluvial carbon flux. Estimated fluxes from the Conwy blanket bog site in Wales over a two year period were 19.3 gC/m^2/yr for DOC, 0.9 gC/m^2/yr for POC and 0.6 gC/m$^{2/}$yr for DIC (Billett *et al.*, 2010).

Dependent on site specific conditions, a summary of the average expected rates of carbon sequestration from a healthy peatland reported in the literature is given below in Table 6-2. It is currently estimated that degraded peatlands in Scotland excluding those used for forestry or agriculture, emit upwards of 6 Mt CO_2e per year (Scottish Government, 2018).

Table 6-2: Rates of carbon sequestration from peatland habitats

The rate of carbon sequestration taken up from the atmosphere can vary over time based on changes to climate, vegetative cover, topographic position and land management (Ferretto *et al.*, 2019). A negative value equates to storage of carbon within the system.

Peatland	Rate of carbon sequestration ($gC/m^2/yr$)	Source
Northern peatland	-23	(Gorham, 1991)
Northern peatlands	-13- -21 $gC/m^2/yr$ / -48- -77 g CO_2 m^{-2} yr^{-1}	(Clymo *et al.*, 1998)
Flow Country	-16.3	(Ratcliffe *et al.*, 2018)
Northern peatland	-18	(Yu *et al.*, 2009)
British and UK peat	-40- -70	(Cannell *et al.*, 1993)
Two UK peatland sites	-56- -72	(Billett *et al.*, 2010)
Range of rates from the last 150 years	-35- -209	(Billett *et al.*, 2010)
European peatlands	-0- -80	(Janssens *et al.*, 2005)

Based on the net ecosystem exchange measurements at Auchencorth Moss, Central Scotland, the peatland shifted from a carbon emitting source of +19.6 $gC/m^2/yr$ in 2003 to a carbon sink providing a net uptake of -136 $gC/m^2/yr$ in 2008 (Dinsmore *et al.*, 2010). This helps to demonstrate that positive land management measures combined with favourable climatic conditions can result in a successful switch to a carbon sequestering peatland. However, it must also be recognised that if erosion continues, the opposite can happen. For example, the shift in Bleaklow Plateau in the southern Pennines from a net sink of carbon of –20.3 gC/m^2 /yr in 1994 to a net source of +29.4 $gC/m^2/yr$ in 2010 (Tallis, 1994; Evans and Lindsay, 2010) is attributed to gully erosion.

As demonstrated at the Mòine Mhór study site, when calculating landscape carbon budgets, it is important to consider the fluvial exports of carbon from the peatland. To conclude, as expected, the highest exports were observed as losses through the DOC component of the carbon budget. The losses calculated as DIC and POC also represented a significant proportion of the budget. Based on the field data collected, the carbon fluxes were reported only for the Mòine Mhór south east tributary. To know if the site is a carbon source, the carbon uptake rates would also need to be quantified. Given the shallow peat depths encountered across the site and the areas of bare peat, it is unrealistic to expect the site to sequester or store carbon at the rate of those other peatlands presented in Table 6-2. Restoration could stabilise, reduce or reverse the carbon fluxes from the site.

6.2 Processes affecting aquatic carbon export

Based on interpretation of the results and field observations during the research (Chapter 3 and Chapter 5), the main processes affecting the aquatic carbon export from the Mòine Mhór have been summarised in Figure 6-2. Other processes that affect peat erosion but were not encountered at the study site over the duration of the project include drainage, fire and peat cutting as previously highlighted in Table 1-1.

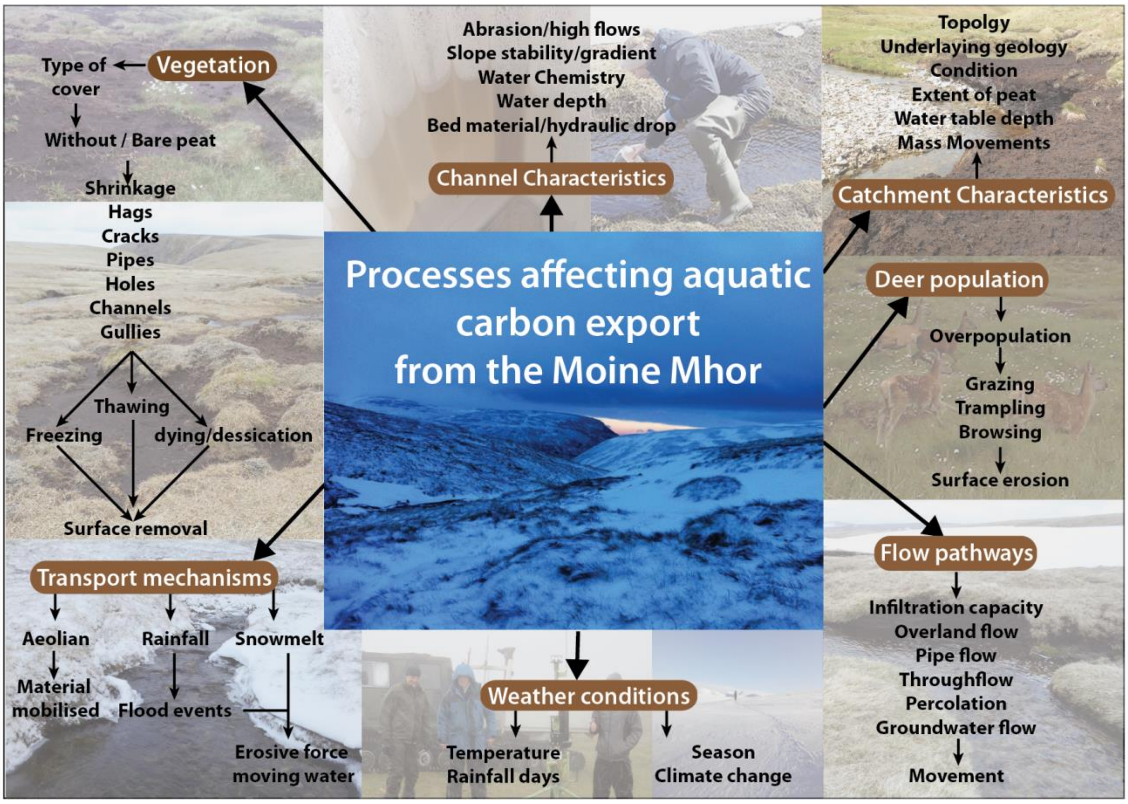


Figure 6-2: Processes affecting aquatic carbon export on the Mòine Mhór

Peatlands, such as the Mòine Mhór are a significant source of fluvial carbon, in the form of DOC, TOC, DIC, POC and dissolved CO_2. Aquatic carbon export from peatlands results from a variety of carbon sources and transport mechanisms as indicated above.

Although not indicated in the figure above, there are many interacting processes such as the influence of temperature and season on the water chemistry. Lower absorbance values occurred in streams when they were covered by the snow. The highest values were observed in the summer months in response to increased temperatures triggering the melting of the snow and the increase in precipitation/storm events. Seasonal patterns were also observed for the other water chemistry parameters monitored as previously discussed in Section 5.6.2. The highest aquatic carbon exports tended to occur in response to heavy rainfall events. The features created from a lack of vegetative cover such as gullies and channels of bare peat, provide flow pathways that facilitate the movement of water thus increasing aquatic carbon export (Holden, 2005c). Deer can also influence aquatic carbon exports at the Mòine Mhór as highlighted above. However, the negative impacts associated with the red deer on the site can be managed through control of their population size (Albon *et al.*, 2007; Sakai *et al.*, 2011).

With reference to the impacts of vegetative cover, a study by Walker and colleagues on a subarctic blanket peat site in northern England located at 550 m AOD found that ecosystem respiration flux was greatest in plots where dwarf shrubs or graminoids were present (Walker *et al.*, 2016). The thawing of permafrost post winter results in an increase in carbon respiration from the peatland surface (Dorrepaal *et al.*, 2009). Indeed, a warming of 1°C was enough to significantly increase the respiration of the peatland carbon, by 111 % in the bare peat plot, by 63 % in the dwarf-shrubs plot, but not from the bryophyte or fully vegetated areas (Walker *et al.*, 2016). This again indicates the importance of revegetating the bare peat areas within the sub-catchments of the Mòine Mhór, moving towards coverage where *Sphagnum* and bog mosses are dominant. This is in contrast to the current situation in which bare peat cover within the catchments varies from 16 % (Garbhlach north east) to 42 % (Caochan Dubh upper) (Figure 3-7). Moreover, it is important to have the correct soil nutrients for positive growth of the plant community which will have a strong control over carbon respiration (Updegraff *et al.*, 2001). From the vegetation encountered on the Mòine Mhór (Section 3.7.1), it can be interpreted that the soil nitrate concentrations are good for bryophytes and lichen to survive and they are well suited to the conditions of the plateau.

The transport mechanisms and weather conditions summarised in Figure 6-2 will influence and shape the condition of the site. The provision of a well vegetated ground surface that minimises surface pathways and its suitability as a carbon sink will reduce the potential vulnerability of the impacts of transport mechanisms and weather conditions on the peatland. This will allow it to withstand the impacts that increase aquatic carbon export from the site. Pipe flow was observed within the study area, particularly in the Caochan Dubh north east and Caochan Dubh north west catchment. The underground pipe network often has the capacity to contribute POC and DOC to the stream as it is a directly connected pathway (Holden *et al.*, 2012). Around 10 %, and at times up to 30 % of streamflow was found to be moving through the pipe network in upland peat catchments in the Pennine Hills of northern England highlighting the potential significance of this contribution to aquatic carbon exports (Holden and Burt, 2002c). At the study site the pipes were located at the bottom of slopes, as also observed in Holden's other studies (Holden *et al.*, 2002; Holden, 2004). However, the observation in the other studies of greater gullying and pipes at the top of the slopes was not observed during this study. In the upper parts of the catchments, the ground cover was often exposed down to its mineral strata such as on the Meall Dubhag summit at 996 m AOD (Table 3-1 and Figure 3-2).

Projected climate change trends for the 21st century include warmer and wetter winters and hotter, drier summers. The increased temperatures may increase the sensitivity of the peat to cracking and drying out and result in a reduction of the water table during the summer months. With lower water tables, a greater percentage of peat will be available for oxidation in biochemical reactions and the decomposition of peat will increase the amount of DOC and CO_2 available for release (Silvola *et al.*, 1996b; Updegraff *et al.*, 2001). This would be less of a concern if there was a mature, established vegetation cover in the peatland habitats.

Under a high emission scenario, the projections are for a reduction in snowfall and lying snow across the UK, with this decrease more prominent in lower lying regions when compared to the mountainous regions (Met Office, 2019a). A reduction in snow cover would impact on the vegetation assemblages observed and the wildlife which relies upon its seasonal patterns. More heavy rainfall over short durations can increase flood risk as surface run-off is increased within the headwater catchments (Met Office, 2019b). As indicated previously, certain conditions for temperature and precipitation are required for peat to grow (Section 2.2) (Ferretto *et al.*, 2019). A changing climate could alter the suitable locations where peat can continue to grow. Small changes can have large impacts on the peatland (Holden, 2005c) and indicates the importance of understanding the site specific processes contributing to the condition of the peatland to maximise the carbon storage potential of the site.

6.3 Restoration and wider implications

Areas of the study site are in a modified condition and other areas would be classified as actively eroding as previously defined in Table 2-3. Overall, observations indicate that the site is currently in poor ecological condition with the forces of water and wind erosion resulting in areas of bare peat. This has been exacerbated by historical overgrazing of the site and exposure to harsh weather conditions. Areas of the mineral strata with isolated vegetation areas were frequently evident on the site across the study catchments (Figure 6-3).

Figure 6-3: Picture taken on the 15th July 2015 within the MM SE T catchment, showing erosion down to the mineral strata with deer resting on the hillside above.

Deer browsing, grazing and trampling may have exacerbated erosion at the site historically, but deer are still a current contributor that requires ongoing management. Herds graze during the summer months on the plateau, moving to lower lying ground in winter. Continued sustainable management of the deer population is required in order to increase the success of the site recovery following any restoration that takes place. If numbers are maintained below 3.5 deer per km^2 the need for fencing may be negated, as found during a study of the impacts of deer on growth of *Pinus sylvestris* (Scots pine) seedlings at Mar Lodge estate, Cairngorms (Rao, 2017). The deer management strategy has to be stringent enough to control the population as the deer can negatively impact on the abundance of species. This can result in a shift in vegetation towards species that are less palatable to the deer with a higher percentage of the browse tolerant species remaining (Dvorak and Catalano, 2016; Owings *et al.*, 2017).

For the Mòine Mhór, if deer are not excluded from the restoration area, brash (arboricultural and forestry residue) could be spread to avoid attracting the deer to the area. The brash layer would also help with avoiding the impacts of frost heave and with stabilising the area. The bare peat area could initially be spread with a seed mix. The brash would then be placed over the top of the area, creating a protective mat, up to 5 cm thick. This thickness has been chosen given the harsher climate and would be spread with some ground left visible. The North Pennines AONB Partnership has successfully used this technique of spreading greatest depths of brash than the more typical 1-2 cm as part of the restoration process. Since 2006, over 1,000 km of ditch blocking works have been successfully undertaken at this northern English upland site. This has resulted in the restoration of over 9,000 hectares of blanket bog costing an estimated £1,000,000. The positive outcome of re-vegetating previously bare peat hagged areas is visible in Figure 6-4 (The AONB Partnership, 2019).

Figure 6-4: Peat hags three years post restoration at the North Pennines (The AONB Partnership, 2019).

For restoring the Mòine Mhór, consideration should be given to the palatability of the vegetation planted. Species like *Deschampsia flexuosa* (wavy hair grass) would be less palatable to the deer and could initially be used as a nurse crop grass. Once stabilised other bog species will be able to colonise the area. This has been successfully used at Bleaklow in the Peak District, an upland blanket bog covering 5,400 ha at 633 m AOD. At Bleaklow, 6,000 dams were blocked and 200 ha of bare peat were successfully revegetated (Moors for the Future Partnership, 2015b).

A five year study by Qassim and colleagues at Bleaklow, Peak District found that in order to avoid a potential deterioration in water quality following revegetation, such as increased DOC exports, consideration should be given to the restoration of the water table and avoidance of liming application which is commonly used alongside fertiliser to aid plant growth (Qassim *et al.*, 2014). Explanations for the increased DOC due to restoration included the solubility of DOC increasing with the increased soil water pH although this reason was concluded as not applicable at Bleaklow (Lumsdon *et al.*, 2005). At Bleaklow, following a fire and subsequent revegetation, it was found that the hydrology of the site was driven by the highly eroded state. After the fire, lower flow pathways in the peat profile became dominant and this continued following the revegetation. Burning of peat can have negative impacts on the peatland ecosystem and is discouraged by many however, the changing climate may mean that the dry weather conditions increase the amount of upland peatland damaged by wildfires (Department for Environment Food and Rural Affairs, 2007; Littlewood *et al.*, 2010). Pore water near the peat surface has lower DOC concentrations whereas the deeper soil water has a higher DOC concentration and higher conductivity when compared with rainwater (Qassim *et al.*, 2014). Restoring the water table would involve blocking any drains or gully features present within the area.

Clear aims and timescales are important for restoration (Littlewood *et al.*, 2010). Therefore, for carrying out the works, restoration should target the areas of bare peat and focus on stabilising them. Hags would be re-profiled to reduce the steepness of their slopes. This would help slow the flow of water, reduce erosion and create a more uniform landscape. Low ground pressure excavators would be required for this task alongside a contractor who has expertise in peatland restoration methods. The excavator works from the top of the hag or section that requires re-profiling and borrows vegetation to fill in the exposed area. The vegetation is then pushed down with the bucket to make sure it is well packed together. This technique was demonstrated by Peatland Action at a restoration workshop event in 2017 at Cairnsmore of Fleet National Nature Reserve, Caste Douglas as shown in Figure 6-5.

Before **After**

Figure 6-5: Hag re-profiling on upland blanket peatland as demonstrated by Drumclog Plant Ltd.

Note that the excavator is working above the hag ‘from the top’. Vegetation was ‘borrowed’ from a well vegetated area upslope of the restored section. The aim was to create a shallow slope which prevents further erosion. Photograph taken in October 2017, following attendance at a Peatland ACTION training programme aimed at contractors.

Whilst carrying out the re-profiling works it would also be of benefit to concurrently look to fill in any gullies and ditches. The main aim is to identify and block the main water flow pathways. The site can be assessed during heavy rainfall to ascertain where the highest flows of water are being transported through the site. The preference would be to use peat from on-site to block flow pathways. However, subject to the damage or depth of the area to be blocked, stone or wood could also be used. The quality of the dams should be checked frequently following the blocking to check that they are holding back water. If required, corrective action should be taken if necessary. The ditch blocks should be holding back water by the end of year one post-blocking with no erosion from ditch over-flow. Evidence of standing water being successfully held behind the ditches following periods of rain and the colonisation and in-filling of vegetation upstream and downstream of the block would be expected by year five (Scottish Natural Heritage, 2019a). Such restoration activities can become effective quite quickly as demonstrated in Figure 6-6.

Note the peat dam technique, vegetated turves have been used to block the ditch and halt the flow of water.

Note the ponding of water observed, the ditch starting to infill and bog mosses beginning to colonise.

Figure 6-6: Post ditch blocking works

The ditch blocking works were undertaken at this previously drained upland site in Southern Scotland in November 2018. This photograph was taken in July 2019 and displays the preliminary success of the works.

For the purposes of budgeting for these works to be undertaken, once on site, it would take around 15-20 minutes per re-profiling section or per ditch block in order to achieve the desired result (Contractors, personal communication, 2017).

Following the ground smoothing and re-profiling works, the next step would then be to revegetate the bare peat areas by planting a range of *Sphagnum* mosses as these are essential for peat formation (van Breemen, 1995; Noble *et al.*, 2019). As indicated previously, the use of brash and nurse crops prior to establishing the desired bog-forming species would increase the chance of success. River banks should also be stabilised if the aim is to conserve the aquatic carbon budget. This is a challenge as any works can be un-done over a season due to the amount of snow and the pressure snowpacks exert on the river banks as demonstrated in Figure 6-7. Focus should be placed on revegetation to effectively stabilise a river bank, so that it would be more capable to withstand the pressure from any melting snowpacks (Environment Agency, 2010). Mats could also be used as a stabilising surface to aid vegetation recovery in suitable areas and in large areas of exposed bare peat.

Figure 6-7: Snowpack melting on the river banks of the CD L

Note the height (~2 m), weight and pressure that this may place on unstable river bank areas. Bank collapse following the spring melt was evident on site, particularly at the Caochan Dubh stream.

The methods outlined above show that multiple restoration methods are required to achieve the desired result of halting the erosion and reducing the flow of water through the site. These works could be supported by Peatland ACTION funding, however, given the low peat depths on the site, this may prove challenging to secure since the carbon stocks are relatively low compared to other sites in Scotland (Scottish Natural Heritage, 2019b). The designations placed on the site, its high altitude and prominent location within the National Park alongside the positive work being undertaken in the lower Feshie would help to make the case for funding for restoration. As indicated previously in Section 3.2.2, areas of the site are classified as a nationally important resource (Class 1 and Class 2).

There is a large expanse of bare peat at the headwater of the Garbhlach north east catchment which could also benefit from re-vegetation. There are areas that were *en-route* to the spectro::lyser site from the track which could also benefit from hag re-profiling. The target outcome is to re-wet the area and restore the water table. Success can be quantified through increase in carbon stored. This could be monitored through peat depth surveys prior to and after the restoration has taken place e.g. 15-20 years later. Stream water sampling for DOC, TOC and POC could also be used to monitor changes and quantify success. Headspace gas samples could also be taken and analysed by GC for concentrations of DIC, CO_2 and CH_4. Increases in water table depth can be monitored through the installation of dipwells across the restored area, although since this is not a drained area, it might not be applicable for monitoring the success of restoration at this site.

As mentioned in the IUCN UK Peatland Strategy, sustainable land management for peatlands will require reviews of current approaches, the provision of further information and capacity building to allow for their sustainable management (International Union for Conservation of Nature, 2018). The goal is to optimise success rates with regards to safeguarding or improving the peatland resource and to carry out activities which work with this strategic goal. The economic viability needs to be considered. If land management had previously been more profitable from activities such as drainage, afforestation, burning, grazing, peat extraction and/or infrastructure development then a change is required to a system which incentivises peatland management. For the study site, it is thought that Glenfeshie estate would work sensitively and positively with regards to the sustainable management of the peatland which would help to optimise its success, given the known importance of conservation to the current owner's vision for the land.

The net effect of restoring Ben Lawers (1214 m AOD) from an actively eroding peatland to a drained or modified condition was estimated to cut emissions by around 20 tonnes CO_2 equivalent per hectare per year. The 0.5 ha area restored by re-profiling and with peat depths ranging from 0.2 to 3.0 metres reduced emissions by 10 tonnes CO_2 equivalent annually and cost £20,000 (Spaven, 2016). Given the high altitude and comparable conditions associated with the Mòine Mhór study site, a switch from actively eroding to stable peatland could reduce emission by 20 tonnes CO_2 equivalent annually on every 1 ha restored. With reference back to Table 6-1, it is realistic that the site following restoration has the potential to become a carbon store and make a carbon saving when compared with the do nothing approach.

Over the longer term, the success of the restoration of the area should be monitored by the health of the bog. This would include a high water table and the presence of peat forming vegetation across the site making it an active bog. An active bog located on depths of peat >0.5 m, would on average be expected to increase in peat depth 0.5-1.0 mm per annum (Farmer, 2008). Given the current condition and status of the site, it is recognised that the requirement for stabilisation is currently the priority goal, with a view to the peat depths accumulating thereafter.

The data presented in this thesis has given an insight into the condition and carbon storage capacity of the peatlands covering the Mòine Mhór, and the fluvial losses from it. As the peatland is in an eroding state, restoration would be required in order to maximise its potential as a carbon store. As the financial cost of doing so may be significant for the current owner, it may best to target a few areas firstly to regenerate, and once these show improved signs of carbon storage, then they could progress with restoring the complete Mòine Mhór catchment.

7. Conclusion

Peatlands are an important carbon store in the UK and sequester atmospheric carbon dioxide when in a favourable condition. The requirement for long term effective carbon storage will be become more relevant over the coming decades due to climate change implications and also to meet international climate change treaties. In order to work optimally, peatlands must be functioning and not eroding which can turn a carbon sink into a carbon source. Degradation by mismanagement and erosion increases the emissions of carbon dioxide (CO_2) and methane (CH_4) from peatlands (Evans and Lindsay, 2010). Consequently, it is important that we understand as much as possible about the extent and condition of the UK's current peatlands to allow optimal management of existing peatlands (Chapter 2 and Chapter 3).

This research has investigated one high altitude upland peatland using a combination of field and laboratory methods (Chapter 4). The main findings of the study (Chapter 5 and Chapter 6) conclude that over 15 % of the site is covered by bare peat with the condition attributable to the forces of water and wind erosion. Historical overgrazing and exposure to harsh weather conditions have exacerbated the current condition, where areas of the mineral strata were frequently evident on the site. Positive signs of ecological recovery are indicated by the native tree regeneration present in the lower glen where the benefit of continued sustainable management of the deer population is evident. Given the Mòine Mohr's upland location, focus should be placed on revegetation to effectively stabilise the river banks, hopefully making the site capable to withstand the pressure from any melting snowpacks.

The results of the monitored water quality were similar across catchments with no one particular stream or parameter standing out on every occasion. However, the least eroded catchments were the Garbhlach east and Garbhlach north east, indicating a possible relationship of lower colour in the less eroded sections of the site. There was also no consistent clear relationship between flow and ecological condition of the catchment however, the Garbhlach north east had the lowest bare peat areas (16 %) and flow rates compared to the other catchments. Based on the field data collected, the carbon fluxes were reported for the Mòine Mhór south east tributary. The DOC flux (20 $gC/m^2/yr$) formed the highest component of the fluvial carbon flux, compared to a measured mean loss of DIC of 5.9 gC/m^2/yr and a mean POC loss of 9.6 gC/m^2/yr. To know if the Mòine Mhór is a carbon source, the carbon uptake rates would also need to be quantified which was out with the scope of this study. Given the estimated values, it is realistic to expect that the site, following restoration, has the potential to become a carbon store and make a carbon saving when compared with the do nothing approach.

The limitations, recommendations and concluding remarks derived from this study are summarised in the following sections.

7.1 Data limitations and future research recommendations

Some of the key difficulties and limitations are summarised in this section whilst also making suggestions of improvements for future research at the Mòine Mhór catchment.

Firstly, from a practical and safety point of view, the absence of the bridge to safely cross the River Feshie in high flow events was a major constraint to the collection of data during storm events. The lack of bridge should also be given consideration when managing the logistics of restoring this remote location. The lack of bridge impacted on the number of samples and flow gaugings taken. An increased sample size with a better emphasis on samples collected/flows measured during a wider range of flow condition events would have benefited the study. The successful set-up of one autosampler proved very useful for the purpose of this project. However, if two autosamplers had been in working order, they could have been deployed in two different catchments to study comparisons between catchments.

There were uncertainties surrounding the water level data collected. This resulted in the level data being excluded from one of the monitored streams, the Caochan Dubh north east. The exploration into the accuracy of the pressure sensors used to derive the water levels and the atmospheric pressure for the site continued beyond the timescale of the project. It would be beneficial to follow up on this with some further experiments which could involve a three-way comparison with an unvented HOBO, vented HOBO and a vented HOBO in a stilling well for example. It was ultimately useful to compare the relationship between the low and high altitude barometric measurements and to introduce the modelled flows captured from a lower point of the catchment which were scaled to the Mòine Mhór catchment. This provided some further comparative datasets to help validate the results collected during this project.

To help answer the research question of what impact the deer had on erosion versus the natural erosional processes at work would have required a control area from which deer were excluded. The idea of a fence was suggested at the start of the project timeline but due to the sensitive nature of the study site (aesthetics and worry of bird strikes) the fence was decided as inappropriate. If deer were excluded from an area of the Mòine Mhór, a greater focus would have taken place on the vegetation in a more structured study. The exclusion of deer from an area was out with the control of this project, although observing how the deer use the Mòine Mhór (behaviour, movements and feeding) without restricting their access proved informative. Glenfeshie estate manages deer population size and although they cannot have complete control, the deer numbers were managed to an extent in the study site. It is acknowledged that the lack of control or no erosion sites for comparison made it difficult to draw conclusions about the effect of deer on the hydrology and erosion encountered at the study site.

Whilst accepting that research projects have a finite budget, in the absence of financial limitations some suggestions follow. It would have been beneficial to have had access to a TOC/DOC analyser for analysis of all samples collected throughout the project. Occasional access was available which meant some samples were analysed for DOC, proving valuable in terms of validating the data collected from the continuous monitor on site, the spectro::lyser. Access to laboratory facilities and resources should be considered in future studies as this does constrain the project and impacts on the amount of data that can be successfully collected throughout the project timescale.

It would have been beneficial to carry out the loss on ignition method where the suspended sediment filter papers would have been ashed at 375 °C to further understand the POC losses from the study site. The collection of spuriously high values for dissolved oxygen collected from the handheld unit also introduced a question of equipment reliability and resulted in uncertainty about these data. With reference to the peat block study (Section 5.10), water depth and flow rate can influence the block movement downstream, with the blocks reducing in size as they are transported downstream to the River Feshie through rolling and abrasive movement. It may have proved interesting to capture how the presence of blocks and size changes if the study was repeated in the headwater streams and then again further downstream. To help distinguish between the amount of blocks encountered under different weather conditions, the blocks could have been pegged or marked to allow identification on a repeat visit (Evans and Warburton, 2001).

Nutrient export was mentioned in the literature review (Section 2.4.1.2). Nutrient availability can limit productivity in *Sphagnum* mires (Malmer and Wallén, 2005), therefore in an eroding peatland this would be of interest to monitor. The interaction of carbon and nutrients in surface waters is complicated but it is known that the fate of exported carbon is determined by the nutrient availability (Waldron *et al.*, 2009). Although the streamwater nitrate concentrations were measured showing that the stream was not nitrogen limited, the fate of aquatic carbon export could be explored further by analysing water samples for soluble reactive phosphorus and total phosphorus concentrations.

A further recommendation would be to configure the spectro::lyser for automatic cleaning as some of the results were unusable due to the optical window becoming dirty. This was particularly evident during the summer months where the sensor was often covered by algae material. Initially it was decided against the automatic cleaning with compressed air due to the need to acquire the extra accessories and in relation to concerns over the battery consumption required. However, the final set-up employed with the solar panels and batteries would, in all likeliness, have met the extra power consumption required for automatic cleaning. It would also have been useful to have the instrument cleaning itself during the winter months when it was inaccessible due to snow cover. This would increase the useable data gained from such an instrument and improve the continuity in gathering a continuous data set on the water quality of the monitored stream. This could have been further supported by a reduction in the amount of suspect data identified with the flow dataset. Operation of the spectro::lyser was challenging due to the remote location of the site, the mobile channel conditions and the amount of time the sensors were encased in snow and ice. Nevertheless, a reasonably complete dataset was captured for the purpose of this study.

Reliability issues were reported in the presentation of the weather station and precipitation data. This resulted in a mix of data sources being utilised for comparison with the water quality monitoring results. A more rapid response when equipment failed may have resulted in a more complete data set however, the data captured was of good quality given the remoteness of the monitoring network.

Although beyond the scope of this project, it would have been interesting to have gathered some data and opinions through stakeholder engagement. The target stakeholders may be people who use or pass through the Mòine Mhór. Questions could include: Do they think there is an issue with deer and bare peat or do they recognise the link between the two? What is their opinion with respect to restoration and land ownership (who pays?). These opinions would be useful if the project is to develop to include a period of disruption where restoration may be conducted. For example, is the restoration something the people who use the landscape would be willing to support? The chances of restoration success may also be optimised by including the people who use the study site in a recreational capacity. Awareness is key as they will be more likely to respect not walking over areas of bare peat or an area which has been re-vegetated if they are informed of the benefits of doing so. The goals of peatland restoration and the benefits need to be communicated to the general public and include stakeholder engagement.

The hydroperiod (the period in which a soil area is waterlogged) (Foti *et al.*, 2012) should be used with data on size to make an informed decision on ranking peatlands for protection or restoration. Water levels rise and fall in a pattern known as the hydroperiod so it might be useful to understand the hydroperiod for the Mòine Mhór. As identified in the literature review (Section 2.7.2), it is often challenging to establish the initial and consequent drivers of erosion (Aalders *et al.*, 2011).

Moving forward, some recommendations for future work would be the creation and implementation of a restoration plan for the site that would include gully blocking and bare peat re-vegetation (Section 6.3). The limited season in which fieldwork could take place in relation to the breeding bird season would need to be considered. However, once the River Feshie has been forded, the track provides easy access to the areas that require restoration. The public benefit to restoring such a visible area would be the reward alongside the carbon benefits. For fieldwork, the complete carbon budget of the site could be better understood which would require a team monitoring approach relating to the water and land environment. These aspects were touched upon within the thesis but not monitored long term enough to characterise the atmospheric and inorganic carbon contributions to the carbon losses from the Mòine Mhór.

The results captured within this study site would be transferable to other upland peatlands sites in the UK or further afield where similarities may lie in either condition or extent of the peatland. The stream flow behaviour and water chemistry results at the study site can be compared with qualitative results from other studies too. The data collected over the years also allowed seasonal trends to be identified, building on further understanding of stream hydrology and water chemistry and how it is impacted under different scenarios. The results are provided for a point in time. Change can be monitored by completing a similar study at a later date, at the same location to monitor how the condition of the site has changed. This study could be repeated to investigate the effect of a changing climate and/or a change in land management.

7.2 Concluding remarks

Scientific research is not conducted in a vacuum and emphasis must be placed on practical implementation based upon research findings. This often requires researchers to pre-empt topical research areas as policy makers often work on quick turnarounds which is often at odds with longer term research timescales. Hydrological understanding is needed alongside policies, frameworks and legislation for protecting the natural heritage of Scotland’s rivers through management techniques aimed at maintaining and enhancing them (Gilvear *et al.*, 2002). This holistic approach is outlined in the EU Water Framework Directive however at an uncertain time in our future in relation to leaving the

EU, emphasis must be placed on the safeguarding of Scottish river water quality. Glenfeshie estate is privately owned and the current owner is not adverse to change and actively promotes the conservation of nature. In these uncertain political times this is something which is reassuring and beneficial to the implementation of action whether, it is the regeneration of the Caledonian pine forest or restoration of the upland peat environment. People are the driver of change and the people who work for, or in collaboration with the landowner have the understanding and force to make, and to continue making the management of the water, land and wildlife environment a success for future generations to come.

Peatland restoration and recovery may take time and scientists need to be proactive in conveying the ecosystem services and benefits celebrating success where it has been achieved. A reduction in DOC can improve water quality, reducing the need for chlorination (Martin-Ortega *et al.*, 2014). A reduction in GHG as a result of restoration can contribute towards the delivery of meeting climate targets and other policies such as the EU Habitats Directive and WFD (Bonn *et al.*, 2014).

8. References

Aalders, I., Hough, R. and Towers, W. (2011). Risk of erosion in peat soils - an investigation using Bayesian belief networks. *Soil Use and Management* **27**, 538–549. doi:10.1111/j.1475-2743.2011.00359.x.

Aalen, F., Whelan, K. and Stout, M. (1997). *Atlas of the Irish Rural Landscape*. Cork University Press, Cork, Ireland.

Abbot, P. (2001). Ireland's Peat Bogs - Accessed at http://www.wesleyjohnston.com/users/ireland/geography/bogs.html.

Ågren, A., Buffam, I., Jansson, M. and Laudon, H. (2007). Importance of seasonality and small streams for the landscape regulation of dissolved organic carbon export. *Journal of Geophysical Research* **112**, 1–11. doi:10.1029/ 2006JG000381.

Agus, F., Hairiah, K. and Mulyani, A. (2011). *Measuring carbon stock in peat soil: practical guidelines*. (ed. World Agroforestry Centre (ICRAF) Southeast Asia Regional Program) Indonesian Centre for Agricultural Land Resources Research and Development, Bogor, Indonesia.

Alamy Stock Photo (2009). A fourteen point imperial red deer stag (Cervus elaphus) in profile, in Richmond Park, Surrey. October - Accessed at https://www.alamy.com/stock-photo-a-fourteen-point-imperial-red-deer-stag-cervus-elaphus-in-profile-47942787.html.

Albon, S., Brewer, M., O'Brien, S., Nolan, A. and Cope, D. (2007). Quantifying the grazing impacts associated with different herbivores on rangelands. *Journal of Applied Ecology* **44**, 1176–1187. doi:10.1111/j.1365-2664.2007.01318.x.

Allan, M. (2010). Water Management: Current Domestic Water Use - Accessed at http://www.esru.strath.ac.uk/EnvEng/Web_sites/09-10/EuropeanSolutions Website/WaterManagement.html. *European Solutions*.

Andersen, R., Chapman, S. J. and Artz, R. R. E. (2013). Microbial communities in natural and disturbed peatlands: A review. *Soil Biology and Biochemistry* **57**, 979–994. doi:10.1016/j.soilbio.2012.10.003.

Anderson, J. (1991). A conceptual framework for evaluating and quantifying naturalness. *Conservation biology* **5**, 347–352.

Armstrong, A., Holden, J., Kay, P., Francis, B., Foulger, M., Gledhill, S., Mcdonald, A. and Walker, A. (2010). The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water ; results from a national survey. *Journal of Hydrology* **381**, 112–120. doi:10.1016/j.jhydrol.2009.11.031.

Artz, R., Donnelly, D., Aitkenhead, M., Balana, B. and Chapman, S. (2013). *WISE Peatland Choices - a decision support tool for peatland restoration in Scotland*.

Artz, R., Donnelly, D., Andersen, R., Mitchell, R., Chapman, S., Smith, J., Smith, P., Cummings, R., Balana, B. and Cuthbert, A. (2014). Managing and restoring blanket bog to benefit biodiversity and carbon balance – a scoping study. *SNH Commissioned Report No. 562*.

Ashworth, P. and Ferguson, R. (1989). Size-selective entrainment of bed-load in gravel bed streams. *Water Resources Research* **25**, 627–634. doi:10.1029/WR025i004p00627.

Avery, B. (1980). Soil Classification for England and Wales (Higher Categories). *Soil Survey Technical Monograph* **14**,.

Babbitt, K. (2005). The relative importance of wetland size and hydroperiod for amphibians in southern New Hampshire, USA. *Wetlands Ecology and Management* **13**, 269–279. doi:10.1007/s11273-004-7521-x.

Bain, C. G., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Kennleyside, C., Labadz, J., Lindsay, R., Littlewood, N., Lunt, P., Miller, C. J., Moxey, A., Orr, H., Reed, M., Smith, P. and Swales, V. (2011). *IUCN UK Commission of Inquiry on Peatlands*. Edinburgh.

Baines, D. (1991). Nordic Society Oikos Factors Contributing to Local and Regional Variation in Black Grouse Breeding Success in Northern Britain. *Scandinavian Journal of Ornithology* **22**, 264–269.

Baines, D., Sage, R. and Baines, M. (1994). The Implications of Red Deer Grazing to Ground Vegetation and Invertebrate Communities of Scottish Native Pinewoods. *Journal of Applied Ecology* **31**, 776–783. doi:10.2307/2404167.

Ball, T., Smith, K. and Moncrieff, J. (2007). Effect of stand age on greenhouse gas fluxes from a Sitka spruce [Picea sitchensis (Bong.) Carr.] chronosequence on a peaty gley soil. *Global Change Biology* **13**, 2128–2142. doi:10.1111/j.1365-2486.2007.01427.x.

Ballard, C., McIntyre, N. and Wheater, H. (2012). Effects of peatland drainage management on peak flows. *Hydrology and Earth System Sciences* **16**, 2299–2310. doi:10.5194/hess-16-

2299-2012.
Barber, K. E., Chambers, F. M. and Maddy, D. (2003). Holocene palaeoclimates from peat stratigraphy: macrofossil proxy-climate records from three oceanic raised peat bogs in England and Ireland. *Quaternary Science Reviews* **22**, 521–539.

Barron, H. F., Gillespie, M. R. and Merritt, J. W. (2011). *Geodiversity of the Cairngorms National Park. British Geological Survey Open Report - Accessed at http://nora.nerc.ac.uk/18475/*.

Barthelmes, A., Couwenberg, J., Risager, M., Tegetmeyer, C. and Joosten, H. (2015). *Peatlands and Climate in a Ramsar context: A Nordic-Baltic Perspective*. Rosen-Schultz Grafisk, Denmark.

Bartram, J. and Ballance, R. (1996). *Water Quality Monitoring - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes*. United Nations Environment Programme and the World Health Organisation.

Bastian, O. and Steinhardt, U. (2002). *Development and Perspectives of Landscape Ecology*. Springer doi:10.1007/978-94-017-1237-8.

Battin, T., Butturini, A. and Sabater, F. (1999). Immobilization and metabolism of dissolved organic carbon by natural sediment biofilms in a Mediterranean and temperate stream. *Aquatic Microbial Ecology* **19**, 297–305. doi:10.3354/ame019297.

Beer, J. and Blodau, C. (2007). Transport and thermodynamics constrain belowground carbon turnover in a northern peatland. *Geochimica et Cosmochimica Acta* **71**, 2989–3002. doi:10.1016/j.gca.2007.03.010.

Beheim, E. (2006). The Effect of Peat Land Drainage and Afforestation on Runoff Dynamics: Consequences on Floods in the Glomma River. *Environmental Role of Wetlands in Headwaters* 59–75.

Belyea, L. and Baird, A. (2006). Beyond "the limit to peat bog browth": Cross-scale feedback in peatland development. *Ecological Monographs* **76**, 299–322. doi:10.1890/07-1861.1.

Bennett, K. (1996). Late-Quaternary vegetation dynamics of the Cairngorms. *Botanical Journal of Scotland* **48**, 51–63.

Bennett, K., Boreham, S., Sharp, M. and Switsur, V. (1992). Holocene History of Environment, Vegetation and Human Settlement on Catta Ness, Lunnasting, Shetland. *Journal of Ecology* **80**, 241–273. doi:10.2307/2261010.

Billett, M., Charman, D., Clark, J., Evans, C., Evans, M., Ostle, N., Worrall, F., Burden, A., Dinsmore, K., Jones, T., McNamara, N., Parry, L., Rowson, J. and Rose, R. (2010). Carbon balance of UK peatlands: current state of knowledge and future research challenges. *Climate Research* **45**, 13–29. doi:10.3354/cr00903.

Billings, W. and Mooney, H. (1968). The ecology of arctic and alpine plants. *Biological Reviews* **43**, 481–529. doi:10.1111/j.1469-185X.1968.tb00968.x.

Bindler, R. (2006). Mired in the past — looking to the future: Geochemistry of peat and the analysis of past environmental changes. *Global and Planetary Change* **53**, 209–221. doi:10.1016/j.gloplacha.2006.03.004.

Birks, H. (1996). Contributions of Quaternanry palaecology to nature conservation. *Journal of Vegetation Science* **7**, 89–98.

Birnie, R., Taylor, E. and Smyth, M.-A. (2017). Peatland Condition Assessment Indicators of Peatland Condition. *Scottish Natural Heritage, Peatland ACTION* 1–8.

Bispo, D., Silva, A., Christofaro, C., Silva, M., Barbosa, M., Silva, B., Barral, U. and Fabris, J. (2016). Hydrology and carbon dynamics of tropical peatlands from Southeast Brazil. *Catena* **143**, 18–25. doi:10.1016/j.catena.2016.03.040.

Black, A. and Burns, J. (2002). Re-assessing the flood risk in Scotland. *Science of the Total Environment* **294**, 169–184. doi:10.1016/S0048-9697(02)00062-1.

Blodau, C. (2002). Carbon cycling in peatlands — A review of processes and controls. *Environmental Reviews* **10**, 111–134. doi:10.1139/a02-004.

Bobbink, R., Hornung, M. and Roelofs, J. (1998). The effect of air-borne nitrogen pollutants on species diversity in natural and semi-natural European vegetation. *Journal of Ecology* **86**, 717–738. doi:DOI 10.1046/j.1365-2745.1998.8650717.x.

Bonn, A., Reed, M. S., Evans, C. D., Joosten, H., Bain, C., Farmer, J., Emmer, I., Couwenberg, J., Moxey, A., Artz, R., Tanneberger, F., von Unger, M., Smyth, M. and Birnie, D. (2014). Investing in nature: Developing ecosystem service markets for peatland restoration. *Ecosystem Services* **9**, 54–65. doi:10.1016/j.ecoser.2014.06.011.

Bord na Móna (2017). Formation and Types of Peatlands - Accessed at http://www.heartland.ie/articles/formation-and-types-peatlands. 2.

Botch, M. and Masing, V. (1983). *Mire ecosystems in the U.S.S.R.* Elsevier Scientific Publishing Company doi:Quoted: Weber, C. 1902. tiber die Vegetation und Entstehung des BochJIoores von Augstuaal in ltaly.

Bower, M. (1960). Peat erosion in the Pennines. *Advancement of Science* **64**, 323–331.

Bowes, D. (1960). A bog-burst in the isle of lewis. *Scottish Geographical Magazine* **76**, 21–23.

doi:10.1080/00369226008735774.
Bradley, R., Milne, R., Bell, J., Lilly, A., Jordan, C. and Higgins, A. (2005). A soil carbon and land use database for the United Kingdom. *Soil Use and Management* **21**, 363–369. doi:10.1079/SUM2005351.
Bragg, O. and Tallis, J. (2001). The sensitivity of peat-covered upland landscapes. *Catena* **42**, 345–360.
Bragg, O., Black, A. and MacDonell, T. (2013). Top Bog: Poster.
Brandstetter, A., Sletten, R, S., Mentler, A. and Wenzel, W. (1996). Estimating dissolved organic carbon in natural waters by UV absorbance (254 nm). *Journal of Plant Nutrition and Soil Science* **159**, 605–607. doi:10.1002/jpln.1996.3581590612.
Bressette, J., Beck, H. and Beauchamp, V. (2012). Beyond the browse line: Complex cascade effects mediated by white-tailed deer. *Oikos* **121**, 1749–1760. doi:10.1111/j.1600-0706.2011.20305.x.
Brooks, S. and Stoneman, R. (1997). *Conserving Bogs – The Management Handbook*. The Stationery Office, Edinburgh.
Bruneau, P. and Johnson, S. (2014). Scotland's peatland - definitions & information resources. *Scottish Natural Heritage Commissioned Report No 701* 62.
Bryder, E. (2012). Wind farm construction on upland peat soils: short-lived or sustained losses of dissolved organic carbon and suspended sediments in drainage waters? *University of Stirling, Biological and Environmental Sciences* **BSc (Hons)**, 1–93.
Bubier, J., Crill, P., Moore, T., Savage, K. and Varner, R. (1998). Seasonal patterns and controls on net ecosystem CO2 exchange in a boreal peatland complex. *Global Biogeochemical Cycles* **12**, 703–714. doi:10.1029/98gb02426.
Bubier, J., Moore, T. and Bledzki, L. (2007). Effects of nutrient addition on vegetation and carbon cycling in an ombrotrophic bog. *Global Change Biology* **13**, 1168–1186. doi:10.1111/j.1365-2486.2007.01346.x.
Buckmaster, C., Bain, S. and Reed, M. (2014). Global Peatland Restoration - demonstrating success. *IUCN UK National Committee Peatland Programme* 64.
Buffam, I., Laudon, H., Temnerud, J., Mörth, C. and Bishop, K. (2007). Landscape-scale variability of acidity and dissolved organic carbon during spring flood in a boreal stream network. *Journal of Geophysical Research: Biogeosciences* **112**, 1–11. doi:10.1029/2006JG000218.
Bullock, M., Nelson, S. and Kemper, W. (1988). Soil Cohesion as Affected by Freezing, Water Content, Time and Tillage. *Soil Science Society of America Journal* **52**, 770. doi:10.2136/sssaj1988.03615995005200030031x.
Bunting, M. (1996). The development of heathland in Orkney, Scotland: pollen records from Loch of Knitchen (Rousay) and Loch of Torness (Hoy). *The Holocene* **6**, 193–212. doi:10.1177/095968369600600206.
Burt, T. (1992). The hydrology of headwater catchments. In: P. Callow and G.E. Petts, eds. River handbooks. Oxford: Blackwell.
Butzler, W. (1986). Cervus elaphus Linnaeus, 1758 – Rothirsch. In Handbuch der Saugetiere Europas, Vol. 2/II. *Niethammer, J. & Krapp, F.* **Wiesbaden**, 107–139.
Byrne, K. and Farrell, E. (2005). The effect of afforestation on soil carbon dioxide emissions in blanket peatland in Ireland. *Forestry* **78**, 217–227. doi:10.1093/forestry/cpi020.
Cairngorm Reindeer (2017). The Cairngorm Reindeer Est 1952: Reindeer Facts - Accessed at http://www.cairngormreindeer.co.uk/Facts.aspx.
Campbell, N. and Reece, J. (2005). *Biology*. Seventh. (ed. Pearson Education Inc) Benjamin Cummings, San Francisco.
Cannell, M., Dewar, R. and Pyatt, D. (1993). Conifer plantations on drained peatlands in Britain: A net gain or loss of carbon? *Forestry: An International Journal of Forest Research* **66**, 353–369. doi:https://doi.org/10.1093/forestry/66.4.353.
Carling, P. (1986). Peat slides in Teesdale and Weardale, northern pennines, July 1983: Description and failure mechanisms. *Earth Surface Processes and Landforms* **11**, 193–206. doi:10.1002/esp.3290110209.
Caseldine, C. and Gearey, B. (2005). A multiproxy approach to reconstructing surface wetness changes and prehistoric bog bursts in a raised mire system at Derryville Bog, Co. Tipperary, Ireland. *The Holocene* **15**, 585–601. doi:10.1191/0959683605hl833rp.
Center for Innovation in Engineering and Science Education (2018). Dissolved Oxygen - Accessed at http://www.k12science.org/curriculum/waterproj/oxygen/.
Chambers, F. (2014). Mires. *Encyclopedia of Environmental Change* **3**, 710. doi:10.4135/9781446247501.n2503.
Chapman, S., Artz, R. and Donnelly, D. (2012). Carbon Savings from Peat Restoration. *ClimateXChange, The James Hutton Institute,* 1–17.
Charman, D. (1994). Late-glacial and Holocene vegetation history of the Flow Country, northern

Scotland. *New Phytologist* **127**, 155–168. doi:10.1111/j.1469-8137.1994.tb04270.x.
Charman, D. (2002). *Peatlands and Environmental Change*. John Wiley & Sons, England.
Chason, D. and Siegel, D. (1986). Hydraulic conductivity and related physical properties of peat, lost river peatland, northern minnesota. *Soil Science* **142**, 91–99.
Chimner, R. and Cooper, D. (2003). Carbon dynamics of pristine and hydrologically modified fens in the southern Rocky Mountains. *Canadian Journal of Botany* **81**, 477–491. doi:10.1139/b03-043.
Clark, J., Lane, S., Chapman, P. and Adamson, J. (2007). Export of dissolved organic carbon from an upland peatland during storm events: Implications for flux estimates. *Journal of Hydrology* **347**, 438–447. doi:10.1016/j.jhydrol.2007.09.030.
Clark, J., Bottrell, S., Evans, C., Monteith, D., Bartlett, R., Rose, R., Newton, R. and Chapman, P. (2010a). The importance of the relationship between scale and process in understanding long-term DOC dynamics. *Science of the Total Environment* **408**, 2768–2775.
Clark, J., Billett, M., Coyle, M., Croft, S., Daniels, S., Evans, C., Evans, M., Freeman, C., Gallego-Sala, A., Heinemeyer, a, House, J., Monteith, D., Nayak, D., Orr, H., Prentice, I., Rose, R., Rowson, J., Smith, J., Smith, P., Tun, Y., Vanguelova, E., Wetterhall, F. and Worrall, F. (2010b). Model inter-comparison between statistical and dynamic model assessments of the long-term stability of blanket peat in Great Britain (1940–2099). *Climate Research* **45**, 227–248. doi:10.3354/cr00974.
Clay, G., Worrall, F., Clark, E. and Fraser, E. (2009). Hydrological responses to managed burning and grazing in an upland blanket bog. *Journal of Hydrology* **376**, 486–495. doi:10.1016/j.jhydrol.2009.07.055.
Clement, S. (2005). The future stability of upland blanket peat following historical erosion and recent re-vegetation - Accessed at http://etheses.dur.ac.uk/2962/.
ClimateXChange (2017). ClimatexChange; Scotland's centre of expertise connecting climate change reserach and policy - Accessed at http://www.climatexchange.org.uk/.
Clymo, R. (1963). Ion exchange in Sphagnum and its relation to bog ecology. *Annals of Botany, New Series* **27**, 309–327.
Clymo, R. (1984). The Limits to Peat Bog Growth. *Philosophical Transactions of the Royal Society London* **303**, 605–654. doi:10.1098/rstb.1984.0002.
Clymo, R., Turunen, J. and Tolonen, K. (1998). Carbon Accumulation in Peatland. *Oikos* **81**, 368. doi:10.2307/3547057.
Conradt, L., Clutton-Brock, T. and Guinness, F. (1999). The relationship between habitat choice and lifetime reproductive success in female red deer. *Oecologia* **120**, 218–224. doi:10.1007/s004420050851.
Consumer Council for Water (2018). How much water do you use? - Accessed at https://www.ccwater.org.uk/households/using-water-wisely/averagewateruse/.
Conway, V. and Millar, A. (1960). The hydrology of some small peat-covered catchments in the northern Pennines. *Journal of the Institute of Water Engineers* **14**, 415–424.
Cooper, D., Kaczynski, K., Slayback, D. and Yager, K. (2015). Growth and Organic Carbon Production in Peatlands Dominated by, Bolivia, South America. *Arctic, Antarctic, and Alpine Research* **47**, 505–510. doi:10.1657/AAAR0014-060.
Cory, R., Ward, C., Crump, B. and Kling, G. (2014). Sunlight controls water column processing of carbon in arctic freshwaters. *Science* **345**, 925–928.
Costa, F. and Bacellar, L. (2007). Analysis of the influence of gully erosion in the flow pattern of catchment streams, Southeastern Brazil. *Catena* **69**, 230–238. doi:10.1016/j.catena.2006.05.007.
Côté, S., Rooney, T., Dussault, J., Tremblay, C. and Waller, D. (2004). Ecological Impacts of Deer Overabundance. *Annual Review of Ecology, Evolution, and Systematics* **35**, 113–147. doi:https://doi.org/10.1146/annurev.ecolsys.35.021103.105725.
Crabtree, B. and Bayfield, N. (1998). Developing sustainability indicators for mountain ecosystems: a study of the Cairngorms, Scotland. *Journal of Environmental Management* **52**, 1–14. doi:10.1006/jema.1997.0159.
Cranfield University (2017). Soil Classification System for England and Wales - Accessed at http://www.landis.org.uk/downloads/classification.cfm. *Land Information System*.
Crawford, R., Jeffree, C. and Rees, W. (2003). Paludification and forest retreat in northern oceanic environments. *Annals of Botany* **91**, 213–226. doi:10.1093/aob/mcf185.
Croke, B., Andrew, F., Spate, J. and Cuddy, S. (2005). *IHACRES User Guide*. Second Edi. (ed. iCAM; School of Resources; Environment and Society) Australia.
Crow, S. and Wieder, R. (2005). Sources of CO2 emission from a northern peatland: Root respiration, exudation, and decomposition. *Ecology* **86**, 1825–1834. doi:10.1890/04-1575.
Crowder, J. and MacPherson, W. (2016). Cairngorm Automatic Weather Station - Accessed at http://cairngormweather.eps.hw.ac.uk/details.htm.
Crowdfunder LTD (2018). Let's make "SCOTLAND: A Rewilding Journey" happen - Accessed at

https://www.crowdfunder.co.uk/rewilding. *Trees for Life*.
Crowe, S. and Warburton, J. (2007). Significance of large peat blocks for river channel habitat and stream organic budgets. *Mires and Peat* **2**, 1–15.
Cummins, R., Donnelly, D., Nolan, A., Towers, W., Chapman, S., Grieve, I. and Birnie, R. (2011). *Peat erosion and the management of peatland habitats*.
Daniels, S. M., Agnew, C. T., Allott, T. E. H. and Evans, M. G. (2008). Water table variability and runoff generation in an eroded peatland, South Pennines, UK. *Journal of Hydrology* **361**, 214–226. doi:10.1016/j.jhydrol.2008.07.042.
Dargie, G., Lewis, S., Lawson, I., Mitchard, E., Page, S., Bocko, Y. and Ifo, S. (2017). Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature* **542**, 86–90. doi:10.1038/nature21048.
Davis, J. (1982). Adsorption of natural dissolved organic matter at the oxide/water interface. *Geochimica et Cosmochimica Acta* **46**, 2381–2393. doi:https://doi.org/10.1016/0016-7037(82)90209-5.
Dawson, J. J. C. and Smith, P. (2007). Carbon losses from soil and its consequences for land-use management. *Science of the Total Environment* **382**, 165–190. doi:10.1016/j.scitotenv.2007.03.023.
Dawson, J., Bakewell, C. and Billett, M. (2001). Is in-stream processing an important control on spatial changes in carbon fluxes in headwater catchments? *Science of the Total Environment* **265**, 153–167. doi:10.1016/S0048-9697(00)00656-2.
Dawson, J., Billett, M., Neal, C. and Hill, S. (2002). A comparison of particulate, dissolved and gaseous carbon in two contrasting upland streams in the UK. *Journal of Hydrology* **257**, 226–246. doi:10.1016/S0022-1694(01)00545-5.
Dawson, J., Soulsby, C., Tetzlaff, D., Hrachowitz, M., Dunn, S. and Malcolm, I. (2008). Influence of hydrology and seasonality on DOC exports from three contrasting upland catchments. *Biogeochemistry* **90**, 93–113. doi:10.1007/s10533-008-9234-3.
De Grandi, G., Mayaux, P., Rauste, Y., Rosenqvist, A., Simard, M. and Saatchi, S. (2000). The Global Rain Forest Mapping Project JERS-1 radar mosaic of tropical Africa: Development and product characterization aspects. *IEEE Transactions on Geoscience and Remote Sensing* **38**, 2218–2233. doi:10.1109/36.868880.
Deflandre, B. and Gagné, J. (2001). Estimation of dissolved organic carbon (DOC) concentrations in nanoliter samples using UV spectroscopy. *Water Research* **35**, 3057–3062. doi:10.1016/S0043-1354(01)00024-0.
Delpippo, M. (2015). An investigation into the perceived effects of red deer density on peatland degradation and flora abundance and diversity with specific interest to the Moine Mhor. *University of Dundee, Geography,* 105.
Department for Environment Food and Rural Affairs (2007). *The Heather and Grass Burning Code*. London.
Dieleman, C., Branfireun, B., Mclaughlin, J. and Lindo, Z. (2015). Climate change drives a shift in peatland ecosystem plant community: Implications for ecosystem function and stability. *Global Change Biology* **21**, 388–395. doi:10.1111/gcb.12643.
Dinsmore, K. and Billett, M. (2008). Continuous measurement and modelling of CO2 losses from a peatland stream during stormflow events. *Water Resources Research* **44**, 1–11. doi:http://dx.doi.org/10.1029/2007WR007284.
Dinsmore, K., Billett, M., Skiba, U., Rees, R., Drewer, J. and Helfter, C. (2010). Role of the aquatic pathway in the carbon and greenhouse gas budgets of a peatland catchment. *Global Change Biology* **16**, 2750–2762. doi:10.1111/j.1365-2486.2009.02119.x.
Dinsmore, K., Wallin, M., Johnson, M., Billett, M., Bishop, K., Pumpanen, J. and Ojala, A. (2013). Contrasting CO2 concentration discharge dynamics in headwater streams: A multi-catchment comparison. *Journal of Geophysical Research: Biogeosciences* **118**, 445–461. doi:10.1002/jgrg.20047.
Dise, N. (2009). Peatland response to global change. *Science* **326**, 810–811.
Dobb, R., Wise, R. and Dean, R. (1972). The use of ultra-violet absorbance for monitoring the total organic carbon content of water and wastewater. *Water Research* **6**, 1173–1180. doi:https://doi.org/10.1016/0043-1354(72)90017-6.
Dorrepaal, E., Toet, S., van Logtestijn, R. S. P., Swart, E., van de Weg, M. J., Callaghan, T. V. and Aerts, R. (2009). Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. *Nature* **460**, 616–619. doi:10.1038/nature08216.
Dreamstime (2007). A 16 point red deer stag of 322 SCI, West Coast, South Island, New Zealand - Accessed at https://www.dreamstime.com/royalty-free-stock-photo-point-stag-profile-red-deer-sci-west-coast-south-island-new-zealand-image36503615.
Dunn, S., Langan, S. and Colohan, R. (2001). The impact of variable snow pack accumulation on a major Scottish water resource. *Science of the Total Environment* **265**, 181–194. doi:10.1016/S0048-9697(00)00658-6.

Dupre, C., Stevens, C., Ranke, T., Bleeker, A., Peppler, L., Gowing, D., Dise, N., Dorland, E., Bobbink, R. and Diekmann, M. (2010). Changes in species richness and composition in European acidic grasslands over the past 70 years: The contribution of cumulative atmospheric nitrogen deposition. *Global Change Biology* **16**, 344–357. doi:10.1111/j.1365-2486.2009.01982.x.

Dvorak, T. and Catalano, A. (2016). Exclusion of introduced deer increases size and seed production success in an island-endemic plant species. *Ecology and Evolution* **6**,. doi:10.1002/ece3.1885.

Dyson, K., Billett, M., Dinsmore, K., Harvey, F., Thomson, A., Piirainen, S. and Kortelainen, P. (2011). Release of aquatic carbon from two peatland catchments in E. Finland during the spring snowmelt period. *Biogeochemistry* **103**, 125–142. doi:10.1007/s10533-010-9452-3.

ECN Data Centre (2017). Meteorology Automatic Weather Station Recording: Data Table - Accessed at http://data.ecn.ac.uk/tsv/results_datatables_annual.asp?mcode=MA.

Edwards, A. and Cresser, M. (1992). Freezing and Its Effect on Chemical and Biological Properties of Soil. *Advances in Soil Science* **18**, 55–79.

Edzwald, J., Becker, W. and Wattier, K. (1985). Surrogate parameters for monitoring organic matter and THM precursors. *Journal of American Water Works Association* **77**, 122–132.

El-Bahi, A. and Inan, D. (1999). A solar still with minimum inclination, coupled to an outside condenser. *Desalination* **123**, 79–83. doi:10.1016/S0011-9164(99)00061-2.

Ellis, C. and Tallis, J. (2001). Climatic control of peat erosion in a North Wales blanket mire. *New Phytologist* **152**, 313–324. doi:10.1046/j.0028-646X.2001.00259.x.

Environment Agency (2010). Managing bank instability and erosion.

Evans, R. (1971). The Need for Soil Conservation. *Area* **3**, 20–23.

Evans, M. and Lindsay, J. (2010). Impact of gully erosion on carbon sequestration in blanket peatlands. *Climate Research* **45**, 31–41. doi:10.3354/cr00887.

Evans, M. and Warburton, J. (2001). Transport and dispersal of organic debris (Peat blocks) in upland fluvial systems. *Earth Surface Processes and Landforms* **26**, 1087–1102. doi:10.1002/esp.256.

Evans, M. and Warburton, J. (2007). *Geomorphology of Upland Peat: Erosion, Form and Landscape Change*. Wiley-Blackwell, UK.

Evans, M., Burt, T., Holden, J. and Adamson, J. (1999). Runoff generation and water table fluctuations in blanket peat: Evidence from UK data spanning the dry summer of 1995. *Journal of Hydrology* **221**, 141–160. doi:10.1016/S0022-1694(99)00085-2.

Evans, M., Warburton, J. and Yang, J. (2006). Eroding blanket peat catchments: Global and local implications of upland organic sediment budgets. *Geomorphology* **79**, 45–57. doi:10.1016/j.geomorph.2005.09.015.

Evans, C., Peacock, M., Green, S., Holden, J., Chapman, P., Lebron, I., Callaghan, N., Grayson, R. and Baird, A. (2018). The impact of ditch blocking on fluvial carbon export from a UK blanket bog. *Hydrological Processes* **32**, 2141–2154. doi:10.1002/hyp.13158.

Farmer, R. (2008). *Active Blanket Bog in Wales*. Brussels.

Fenner, C., Evans, C. D., Monteith, D. T., Reynolds, D. and Fenner, N. (2001). Export of organic carbon from peat soils. *Nature* **412**, 785–786.

Ferone, J. and Devito, K. (2004). Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plains topographic gradient. *Journal of Hydrology* **292**, 75–95. doi:10.1016/j.jhydrol.2003.12.032.

Ferretto, A., Brooker, R., Aitkenhead, M., Matthews, R. and Smith, P. (2019). Potential carbon loss from Scottish peatlands under climate change. *Regional Environmental Change* **19**, 2101–2111. doi:10.1007/s10113-019-01550-3.

Fiebig, D. and Lock, M. (1991). Immobilization of dissolved organic matter from groundwater discharging through the stream bed. *Freshwater Biology* **26**, 45–55. doi:10.1111/j.1365-2427.1991.tb00507.x.

Fielding, A. and Haworth, P. (1999). *Upland Habitats: habitat guides*. First. Routledge, London.

Fisher, T., Hagy, J. and Rochelle-Newall, E. (1998). Dissolved and particulate organic carbon in Chesapeake Bay. *Estuaries* **21**, 215–229. doi:10.2307/1352470.

Fluck, R. (1992). *Energy in Farm Production*. Volume 6. (ed. Stout, B.) Elsevier Science Publishers B.V, The Netherlands.

Flux, J. (1970). Life history of the Mountain hare (Lepus timidus scoticus) in north-east Scotland. *Journal of Zoology* **161**, 75–123. doi:10.1111/j.1469-7998.1970.tb02171.x.

Fondriest Environmental Inc (2016). Conductivity, Salinity & Total Dissolved Solids - Accessed at http://www.fondriest.com/environmental-measurements/parameters/water-quality/conductivity-salinity-tds/. *Water Quality*.

Forest Policy Group (2016). A brief history of “the deer problem” in Scotland - Accessed at http://www.forestpolicygroup.org/blog/a-brief-history-of-the-deer-problem-in-scotland/.

Forestry Commission (2016). Organo-mineral Soils - Accesssed at https://www.forestry.gov.uk/forestry/INFD-8J3QRL.

Foti, R., del Jesus, M., Rinaldo, A. and Rodriguez-Iturbe, I. (2012). Hydroperiod regime controls the organization of plant species in wetlands. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 19596–19600. doi:10.1073/pnas.1218056109.

Foulds, S. A. and Warburton, J. (2007). Wind erosion of blanket peat during a short period of surface desiccation (North Pennines , Northern England). *Earth Surface Processes and Landforms* **488**, 481–488. doi:10.1002/esp.

Francis, I. (1990). Blanket peat erosion in a mid-wales catchment during two drought years. *Earth Surface Processes and Landforms* **15**, 445–456. doi:10.1002/esp.3290150507.

Freeman, C., Evans, C., Montieth, D., Reynolds, B. and Fenner, N. (2001). Export of organic carbon from peat soils. *Nature* **412**, 785–785.

Funk, D., Pullman, E., Peterson, K. and Billings, W. (1994). Influence of water table on carbon dioxide, carbon monoxide, and methane fluxes from taiga bog microcosms. *Global Biogeochemical Cycles* **8**, 271–278.

Galbraith, H., Murray, S., Rae, S., Whitfield, D. and Thompson, D. (1993). Numbers and distribution of Dotterel Charadrius morinellus breeding in Great Britain. *Bird Study* **40**, 161–169. doi:10.1080/00063659309477179.

Gallego-Sala, A. V, Charman, D. J., Harrison, S. P., Li, G. and Prentice, I. C. (2016). Climate-driven expansion of blanket bogs in Britain during the Holocene. *Climate of the Past* **12**, 129–136. doi:10.5194/cp-12-129-2016.

Garnett, M., Dinsmore, K. and Billett, M. (2012). Annual variability in the radiocarbon age and source of dissolved CO2 in a peatland stream. *Science of the Total Environment* **427–428**, 277–285. doi:10.1016/j.scitotenv.2012.03.087.

Gaveau, D., Salim, M., Hergoualc'H, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. and Sheil, D. (2014). Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: Evidence from the 2013 Sumatran fires. *Nature Scientific Reports* **4**, 1–7. doi:10.1038/srep06112.

Georgakakos, K. and Hudlow, M. (1984). Design of national real-time warning systems with capability for site-specific flash flood forecasts. *Bulletin of the American Meteorological Society* **67**, 1233–1239. doi:10.1175/1520-0477(1986)067<1233:otdonr>2.0.co;2.

Georgii, B. and Schröder, W. (1982). Home range and activity patterns of male red deer (Cervus elaphus L.) in the alps. *Oecologia* **58**, 238–248. doi:10.1007/BF00399224.

Gibbins, C., Dilks, C., Malcolm, R., Soulsby, C. and Juggins, S. (2001). Invertebrate communities and hydrological variation in Cairngorm mountain streams. *Hydrobiologia* **462**, 205–219. doi:10.1023/A:1013102704693.

Gilbert, O. (1974). Reindeer Grazing in Britain. *Lichenologist* **6**, 165–167. doi:10.1017/S0024282974000272.

Gilvear, D., Heal, K. and Stephen, A. (2002). Hydrology and the ecological qualit of Scottish river ecosystems. *The Science of the Total Environment* **294**, 131–159.

Giusti, L. and Neal, C. (1993). Hydrological pathways and solute chemistry of storm runoff at Dargall Lane, southwest Scotland. *Journal of Hydrology* **142**, 1–27. doi:10.1016/0022-1694(93)90002-Q.

Golledge, N., Hubbard, A. and Sugden, D. (2008). High-resolution numerical simulation of Younger Dryas glaciation in Scotland. *Quaternary Science Reviews* **27**, 888–904. doi:10.1016/j.quascirev.2008.01.019.

Gomi, T., Sidle, R. and Richardson, J. (2002). Understanding Processes and Downstream Linkages of Headwater Systems. *BioScience* **52**, 905–916. doi:10.1641/0006-3568(2002)052[0905:UPADLO]2.0.CO;2.

Gordon, J., Wignall, R., Brazier, N. and Bruneau, P. (2006). *Cairngorms, a landscape fashioned by geology*. Second. SNH Publication, Perth.

Gorham, E. (1984). Acid rain: an overview. *Meteorological aspects of acid rain* 1–18.

Gorham, E. (1991). Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming. *Ecological Applications* **1**, 182–195.

Gotmark, F. (1992). Naturalness as an evaluation criterion in nature conservation: a response to Anderson. *Conservation biology* **6**, 455–458.

Gowlett, J., Hedges, R., Law, I. and Perry, C. (1986). Radiocarbon Dates from the Oxford AMS System: Archaeometry Datelist 4. *Archaeometry* **2**, 206–221.

Gravelle, R. (2015). Discharge Estimation: Techniques and Equipment. *Geomorphological Techniques* **5**, 1–8.

Grayson, R. and Holden, J. (2016). Improved automation of dissolved organic carbon sampling for organic-rich surface waters. *Science of the Total Environment* **543**, 44–51. doi:10.1016/j.scitotenv.2015.10.149.

Grayson, R., Holden, J. and Rose, R. (2010). Long-term change in storm hydrographs in

response to peatland vegetation change. *Journal of Hydrology* **389**, 336–343. doi:10.1016/j.jhydrol.2010.06.012.
Grieve, I. (2000). Effects of human disturbance and cryoturbation on soil iron and organic matter distributions and on carbon storage at high elevations in the Cairngorm Mountains, Scotland. *Geoderma* **95**, 1–14. doi:10.1016/S0016-7061(99)00060-9.
Grieve, I. and Gilvear, D. (2008). Effects of wind farm construction on concentrations and fluxes of dissolved organic carbon and suspended sediment from peat catchments at Braes of Doune, central Scotland. *Mires and Peat* **4**, 1–11.
Grieve, I., Davidson, D. and Gordon, J. (1995). Nature, extent and severity of soil erosion in upland Scotland. *Land Degradation and Development* **6**, 41–55. doi:10.1002/ldr.3400060105.
Grimble, A. (1901). *Deer-stalking and the deer-forests of Scotland. London, Kegan Paul, Trench & Trubner.* London Kegan Paul Trench Trubner & Co Ltd.
Guo, L. and Gifford, R. (2002). Soil carbon stocks and land use change: A meta analysis. *Global Change Biology* **8**, 345–360. doi:10.1046/j.1354-1013.2002.00486.x.
Haigh, M. (2006). *Environmental Change in Headwater Peat Wetlands, UK*. doi:10.1007/1-4020-4228-0_21.
Halliday, S., Wade, A., Skeffington, R., Neal, C., Reynolds, B., Rowland, P., Neal, M. and Norris, D. (2012). An analysis of long-term trends, seasonality and short-term dynamics in water quality data from Plynlimon, Wales. *Science of the Total Environment* **434**, 186–200. doi:10.1016/j.scitotenv.2011.10.052.
Hamada, Y., Tsuji, N., Kojima, Y., Qirom, M., Sulaiman, A., Firmanto, Jagau, Y., Irawan, D., Naito, R. and Nirmala Sari, E. (2016). *Guidebook for estimating carbon emissions from tropical peatlands in Indonesia*. Indonesia.
Hanna Instruments (1995). *Instruction Manual HI 9143, HI 9143M HI 9145 Portable Waterproof Microprocessor Dissolved Oxygen Meters*. Rhode Island, USA.
Hanna Instruments (1996). *Instrcution Manual HI 9033 - HI 9034 HI 9039 - HI 9130 HI 933100 - HI 9635 Portable Waterproof Conductivity / TDS / Fertilizer Meters*. Rhode Island, USA.
Hanna Instruments (1999). *Instruction Manual HI 98140 - HI 98150 HI 99144 Portable Waterproof Microprocessor Logging GLP pH/ ORP Meters*. Rhode Island, USA.
Harris, A. (1972). Infiltration rate as affected by soil freezing under three cover types. *Soil Science Society Proc.* **36**, 489–492.
Harrison, S., Rowan, A., Glasser, N., Knight, J., Plummer, M. and Mills, S. (2014). Little Ice Age glaciers in Britain: Glacier-climate modelling in the Cairngorm Mountains. *The Holocene* **24**, 135–140. doi:10.1177/0959683613516170.
Helliwell, R., Soulsby, C., Ferrier, R., Jenkins, A. and Harriman, R. (1998). Influence of snow on the hydrology and hydrochemistry of the Allt a' Mharcaidh, Cairngorm mountains, Scotland. *Science of the Total Environment* **217**, 59–70. doi:10.1016/S0048-9697(98)00165-X.
Herschy, R. (1995). *Streamflow Measurement*. 2nd Editio. Taylor and Francis, London.
Hewson, R. (1976). A Population Study of Mountain Hares (Lepus timidus) in North-East Scotland from 1956-1969. *Journal of Animal Ecology* **45**, 395.
Hewson, R. and Hinge, M. (1990). Characteristics of the home range of mountain hares Lepus timidus. *Journal of Applied Ecology* **27**, 651–666.
Hmwe, S., Zachos, F., Sale, J., Rose, H. and Hartl, G. (2006). Genetic variability and differentiation in red deer (Cervus elaphus) from Scotland and England. *Journal of Zoology* **270**, 479–487. doi:10.1111/j.1469-7998.2006.00123.x.
Hobbie, S. (1992). Effects of plant species on nutrient cycling. *Trends in ecology & evolution* **7**, 336–339. doi:10.1016/0169-5347(92)90126-V.
Hoffer-French, K. and Herman, J. (1989). Evaluation of hydrological and biological influences on CO2 fluxes from a karst stream. *Journal of Hydrology* **108**, 189–212. doi:10.1016/0022-1694(89)90283-7.
Holden, J. (2004). Hydrological connectivity of soil pipes determined by ground-penetrating radar tracer detection. *Earth Surface Processes and Landforms* **29**, 437–442. doi:10.1002/esp.1039.
Holden, J. (2005a). Piping and woody plants in peatlands: Cause or effect? *Water Resources Research* **41**, 1–10. doi:10.1029/2004WR003909.
Holden, J. (2005b). Controls of soil pipe frequency in upland blanket peat. *Journal of Geophysical Research: Earth Surface* **110**, 1–11. doi:10.1029/2004JF000143.
Holden, J. (2005c). Peatland hydrology and carbon release: Why small-scale process matters. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **363**, 2891–2913. doi:10.1098/rsta.2005.1671.
Holden, J. (2005d). Peatland hydrology and carbon release: why small-scale process matters. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **363**, 2891 LP-2913.
Holden, J. (2009). Flow through macropores of different size classes in blanket peat. *Journal of*

Hydrology **364**, 342–348.

Holden, J. and Burt, T. (2002a). Infiltration, runoff and sediment production in blanket peat catchments: Implications of field rainfall simulation experiments. *Hydrological Processes* **16**, 2537–2557. doi:10.1002/hyp.1014.

Holden, J. and Burt, T. (2002b). Laboratory experiments on drought and runoff in blanket peat. *European Journal of Soil Science* **53**, 675–689. doi:10.1046/j.1365-2389.2002.00486.x.

Holden, J. and Burt, T. (2002c). Piping and pipeflow in a deep peat catchment. *Catena* **48**, 163–199. doi:10.1016/S0341-8162(01)00189-8.

Holden, J. and Burt, T. (2003a). Hydraulic conductivity in upland blanket peat: Measurement and variability. *Hydrological Processes* **17**, 1227–1237. doi:10.1002/hyp.1182.

Holden, J. and Burt, T. (2003b). Hydrological studies on blanket peat: the significance of the acrotelm-catotelm model. *Journal of Ecology* **91**, 86–102. doi:10.1046/j.1365-2745.2003.00748.x.

Holden, J., Burt, T. and Vilas, M. (2002). Application of ground-penetrating radar to the identification of subsurface piping in blanket peat. *Earth Surface Processes and Landforms* **27**, 235–249. doi:10.1002/esp.316.

Holden, J., Chapman, P. and Labadz, J. (2004). Artificial Drainage of Peatlands: Hydrological and Hydrochemical Process and Wetland Restoration. *Progress in Physical Geography* **28**, 95–123. doi:10.1017/CBO9781107415324.004.

Holden, J., Evans, M., Burt, T. and Horton, M. (2006). Impact of land drainage on peatland hydrology. *Journal of Environmental Quality* **35**, 1764–1778. doi:https://doi.org/10.2134/jeq2005.0477.

Holden, J., Chapman, P., Evans, M., Hubacek, K., Kay, P. and Warburton, J. (2007a). Vulnerability of Organic Soils in England and Wales. Final technical report to DEFRA.

Holden, J., Gascoign, M. and Bosanko, N. (2007b). Erosion and natural revegetation associated with surface land drains in upland peatlands. *Earth Surface Processes and Landforms* **32**, 1547–1559.

Holden, J., Kirkby, M., Lane, S., Milledge, D., Brookes, C., Holden, V. and McDonald, A. (2008). Overland flow velocity and roughness properties in peatlands. *Water Resources Research* **44**, 1–11. doi:10.1029/2007WR006052.

Holden, J., Smart, P., Dinsmore, K. and Baird, A. (2012). Morphological change of natural pipe outlets in blanket peat. *Earth Surface Processes and Landforms* **37**, 109–118.

Hope, D., Billett, M. and Cresser, M. (1994). A review of the export of carbon in river water: Fluxes and processes. *Environmental Pollution* **84**, 301–324. doi:10.1016/0269-7491(94)90142-2.

Hope, D., Dawson, J., Cresser, M. and Billett, M. (1995). A method for measuring free CO2 in upland streamwater using headspace analysis. *Journal of Hydrology* **166**, 1–14. doi:https://doi.org/10.1016/0022-1694(94)02628-O.

Hope, D., Billett, M. and Cresser, M. (1997). Exports of organic carbon in two river systems in NE Scotland. *Hydrological Processes* **11**, 325–344. doi:10.1016/S0022-1694(96)03150-2.

Hope, D., Palmer, S., Billett, M. and Dawson, J. (2004). Variations in dissolved CO2 and CH4 in a first-order stream and catchment: an investigation of soil–stream linkages. *Hydrological Processes* **18**, 3255–3275. doi:10.1002/hyp.5657.

Horsfield, D. and Thompson, D. *The uplands: guidance on terminology regarding altitudinal zonation and related terms*.

House, J., Orr, H., Clark, J., Gallego-Sala, A., Freeman, C., Prentice, I. and Smith, P. (2010). Climate change and the British Uplands: evidence for decision-making. *Climate Research* **45**, 3–12. doi:10.3354/cr00982.

Howard, D. and Howard, P. (1993). Relationships between CO2 evolution, moisture content and temperature for a range of soil types. *Soil Biology and Biochemistry* **25**, 1537–1546. doi:10.1016/0038-0717(93)90008-Y.

Hribljan, J., Cooper, D., Sueltenfuss, J., Wolf, E., Heckman, K., Lilleskov, E. and Chimner, R. (2015). Carbon storage and long-term rate of accumulation in high-altitude Andean peatlands of Bolivia. *Mires and Peat* **15**, 1–14.

Hromadka, T., Guymon, G. and Berg, R. (1981). Some approaches to modeling phase change in freezing solis. *Cold Regions Science and Technology* **4**, 137–145.

Hulbert, I., Iason, G., Elston, D. and Racey, P. (1996). Home-range sizes in a stratified upland landscape of two lagomorphs with different feeding strategies. *Journal of Applied Ecology* **33**, 1479–1488. doi:10.2307/2404786.

Iason, G. (1990). The effects of size, age and a cost of early breeding on reproduction in female mountain hares. *Holarctic Ecology* **13**, 81–89. doi:10.1111/j.1600-0587.1990.tb00592.x.

Ingram, H. (1978). Soil layers in mires: function and terminology. *Journal of Soil Science* **29**, 224–227.

Intergovernmental Panel on Climate Change (2013). *Working Group I Contribution to the IPC;*

Climate Change 2013: The Physical Science Basis. Geneva; Switzerland doi:10.1017/CBO9781107415324.Summary.
International Peatland Society (2017). What is peat? - Accessed at http://www.peatsociety.org/peatlands-and-peat/what-peat.
International Union for Conservation of Nature (2014). Peat Bog Ecosystems: Key Definitions. *IUCN UK Committee Peatland Programme Briefing Note Complete set 1-10,* 56.
International Union for Conservation of Nature (2017). Peatland Programme; BogFest 2017: Statistics , Sessions and Messages. *IUCN UK Peatland Programme,* 5.
International Union for Conservation of Nature (2018). *UK Peatland Strategy 2018 - 2040*.
Irish Peatland Conservation Council (2017). Blanket Bogs - Accessed at http://www.ipcc.ie/a-to-z-peatlands/blanket-bogs/.
Irvine, R. (2011). *Sustainable Upland Management A summary of research outputs from the Scottish Government's "Environment - Land Use and Rural Stewardship" research programme*. Aberdeen.
Ivanov, K. E. (1981). *Water movement in mirelands*. Academic Press, London.
Janssens, I., Freibauer, A., Schlamadinger, B., Ceulemans, R., Ciais, P., Dolman, A. ., Heimann, M., Nabuurs, G., Smith, P. and Valentini, R. (2005). The carbon budget of terrestrial ecosystems at country scale; a European case study. *Biogeosciences* **2**, 15–26. doi:10.5194/bgd-1-167-2004.
Jinsheng, G. (2009). *Coal Oil Shale Natural Bitumen Heavy Oil And Peat*. Voulme II. EOLSS Publications.
Johnson, M., Billett, M., Dinsmore, K., Wallin, M., Dyson, K. and Jassal, R. (2010). Direct and continuous measurement of dissolved carbon dioxide in freshwater aquatic systems—method and applications. *Ecohydrology* **3**, 68–78. doi:10.1002/eco.95.
Joint Nature Conservation Committee (2011). Towards an assessment of the state of UK Peatlands. *JNCC Report No. 445* 82.
Joint Nature Conservation Committee (2015). Guidelines for the selection of biological SSSI's. 36.
Joint Nature Conservation Committee (2017). Habitat account - Raised bogs and mires and fens - Accessed at http://jncc.defra.gov.uk/ProtectedSites/SACselection/habitat.asp?FeatureIntCode=H7130.
Jones, J. (2004). Implications of natural soil piping for basin management in upland Britain. *Land Degradation and Development* **15**, 325–349. doi:10.1002/ldr.618.
Jones, J. and Mulholland, P. (1998). Influence of drainage basin topography and elevation on carbon dioxide and methane supersaturation of stream water. *Biogeochemistry* **40**, 57–72. doi:10.1023/A:1005914121280.
Joosten, H. and Clarke, D. (2002). *Wise use of mires and peatlands - Background and principles including a framework for decision-making*. International Mire Conservation Group and International Peat Society, UK.
Joss, A., Davidson, M., Ho-Yen, D. and Ludbrook, A. (2003). Lyme disease - What is the cost for Scotland? *Public Health* **117**, 264–273. doi:10.1016/S0033-3506(03)00067-2.
Kay, A. (2016). A review of snow in Britain: The historical picture and future projections. *Progress in Physical Geography* **40**, 676–698. doi:10.1177/0309133316650617.
Keegan, M. and Daniels, M. (2013). *Scottish Wildlife Trust / John Muir Trust Joint: Sustainable deer management*.
Kirkbride, M., Everest, J., Benn, D., Gheorghiu, D. and Dawson, A. (2014). Late-Holocene and Younger Dryas glaciers in the northern Cairngorm Mountains, Scotland. *The Holocene* **24**, 141–148. doi:10.1177/0959683613516171.
Kling, G., Kipphut, G. and Miller, M. (1991). Arctic lakes and streams as gas conduits to the atmosphere: implications for tundra carbon budgets. *Science* **251**, 298–301. doi:10.1126/science.251.4991.298.
Koehler, A., Murphy, K., Kiely, G. and Sottocornola, M. (2009). Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South Western Ireland. *Biogeochemistry* **95**, 231–242. doi:10.1007/s10533-009-9333-9.
Labadz, J., Allott, T., Evans, M., Butcher, D., Billett, M., Yallop, A., Jones, P., Innerdale, M., Harmon, N., Bradbury, R., Mount, D., Brien, H. and Hart, R. (2010). Peatland Hydrology. *Draft Scientific Review* 3–169.
Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science* **304**, 1623–1627. doi:10.1126/science.1097396.
Lamers, L., Bobbink, R. and Roelofs, J. (2000). Natural nitrogen filter fails in polluted raised bogs. *Global Change Biology* **6**, 583–586. doi:10.1046/j.1365-2486.2000.00342.x.
Langan, S., Johnston, L., Donaghy, M., Youngson, A., Hay, D. and Soulsby, C. (2001). Variation in river water temperatures in an upland stream over a 30-years period. *Science of the Total Environment* **265**, 195–207. doi:10.1016/S0048-9697(00)00659-8.

Langbein, J. (2007). National Deer-Vehicle Collisions Project England (2003-2005). *Deer Initiative Research Report 07/1* 94.

Larsen, E., KB, O. and Emanouilov, V. (2018). Average Daily Water Usage - Accessed at http://www.theworldcounts.com/stories/average-daily-water-usage. *The World Counts*.

Lehmitz, R. (2014). The oribatid mite community of a German peatland in 1987 and 2012-effects of anthropogenic desiccation and afforestation. *Soil Organisms* **86**, 131–145.

Lehrsch, G. (1998). Freeze-thaw cycles increase near-surface aggregate stability. *Soil Science* **163**, 63–70. doi:10.1097/00010694-199801000-00009.

Lent, P. (1965). Observations on antler shedding by female barren-ground caribou. *Canadian Journal of Zoology* **43**, 553–558.

Lenton, T. (2012). Arctic climate tipping points. *Ambio* **41**, 10–22. doi:10.1007/s13280-011-0221-x.

Leopold, A., Sowls, L. and Spencer, D. (1947). A Survey of Over-Populated Deer Ranges in the United States. *The Journal of Wildlife Management* **11**, 162–177.

Letts, M., Roulet, N., Comer, N., Skarupa, M. and Verseghy, D. (2000). Parametrization of peatland hydraulic properties for the Canadian land surface scheme. *Atmosphere-Ocean* **38**, 141–160. doi:10.1080/07055900.2000.9649643.

Lewis, C., Albertson, J., Zi, T., Xu, X. and Kiely, G. (2013). How does afforestation affect the hydrology of a blanket peatland? A modelling study. *Hydrological Processes* **27**, 3577–3588. doi:10.1002/hyp.9486.

Li, P. (2014). Modelling blanket peat erosion under environmental change. *The University of Leeds, School of Geography,* 291.

Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., Roulet, N., Rydin, H. and Schaepman-Strub, G. (2008). Peatlands and the carbon cycle: from local processes to global implications – a synthesis. *Biogeosciences* **5**, 1475–1491.

Lindsay, R. (2009). Expert workshop to establish the current state of knowledge of and future evidence needs for the extent and condition of carbon stocks in Scottish peatlands - Accessed at http://www.gov.scot/Publications/2010/02/19145611/13.

Lindsay, R. (2010). *Peatbogs and Carbon A critical synthesis*. Technical Report, University of East London.

Lindsay, R. and Immirzi, P. (1996). An inventory of lowland raised bogs in Great Britain. *Scottish Natural Heritage Research, Survey and Monitoring Report* **No 78**, 94.

Lindsay, R., Charman, D., Everingham, F., O'Reilly, R., Palmer, M., Rowell, T. and Stroud, D. (1988). *The flow country - The peatlands of Caithness and Suhterland - Part I: Peatland ecology*.

Lindsay, R., Birnie, R. and Clough, J. (2016). Briefing Note No 11. Peatland restoration. *IUCN UK Committee Peatland Programme* 8.

Littlewood, N., Anderson, P., Artz, R., Bragg, O., Lunt, P. and Marrs, R. (2010). *Peatland Biodiversity*.

Loisel, J., Yu, Z., Parsekian, A., Nolan, J. and Slater, L. (2013). Quantifying landscape morphology influence on peatland lateral expansion using ground-penetrating radar (GPR) and peat core analysis. *Journal of Geophysical Research: Biogeosciences* **118**, 373–384. doi:10.1002/jgrg.20029.

Lomas-Clarke, S. and Barber, K. (2007). Human impact signals from peat bogs - A combined palynological and geochemical approach. *Vegetation History and Archaeobotany* **16**, 419–429. doi:10.1007/s00334-006-0085-3.

Lowe, V. (1961). A discussion on the history, present status, and future conservation of red deer (Cervus elaphus L) in Scotland. *Terre Vie* **1**, 9–40.

Lucchese, M., Waddington, J., Poulin, M., Pouliot, R., Rochefort, L. and Strack, M. (2010). Organic matter accumulation in a restored peatland: Evaluating restoration success. *Ecological Engineering* **36**, 482–488. doi:10.1016/j.ecoleng.2009.11.017.

Lumsdon, D., Stutter, M., Cooper, R. and Manson, J. (2005). Model assessment of biogeochemical controls on dissolved organic carbon partitioning in an acid organic soil. *Environmental Science and Technology* **39**, 8057–8063. doi:10.1021/es050266b.

Macrae, G. (2018). Young Red Deer - Accessed at http://shop.photo4me.com/416521/canvas.

Malmer, N. and Wallen, B. (1999). The Dynamics of Peat Accumulation on Bogs: Mass Balance of Hummocks and Hollows and Its Variation Throughout a Millennium. *Ecography* **22**, 736–750. doi:10.1111/j.1600-0587.1999.tb00523.x.

Malmer, N. and Wallén, B. (2005). Nitrogen and phosphorus in mire plants: Variation during 50 years in relation to supply rate and vegetation type. *Oikos* **109**, 539–554. doi:10.1111/j.0030-1299.2001.13835.x.

Maltby, E. and Barker, T. (2009). *The Wetlands Handbook, 2 Volume Set*. First. Wiley-Blackwell, West Sussex.

Mandernack, K. W., Lynch, L., Krouse, H. R. and Morgan, M. D. (2000). Sulfur cycling in wetland peat of the New Jersey Pinelands and its effect on stream water chemistry.

Geochimica et Cosmochimica Acta **64**, 3949–3964.
Mariner, M., Glatzel, S. and Moore, T. (2004). The role of cotton-grass (Eriophorum vaginatum) in the exchange of CO2 and CH4 at two restored peatlands, eastern Canada. *Écoscience* **11**, 141–149.
Marsden, K. and Ebmeier, S. (2012). SPICe Briefing. Peatlands and Climate Change. *SPICe The Information Centre,* 36.
Marsh, T. and Hannaford, J. (2008). *UK Hydrometric Register. Hydrological data UK series*.
Marshall, M. (2013). *Glen Feshie - the History and Archaeology of a Highland Glen*. Second. North of Scotland Archaeological Society, Inverness.
Martin-Ortega, J., Allott, T. E. H., Glenk, K. and Schaafsma, M. (2014). Valuing water quality improvements from peatland restoration: Evidence and challenges. *Ecosystem Services* **9**, 34–437. doi:10.1016/j.ecoser.2014.06.00.
Martin-Ortega, J., Glenk, K. and Byg, A. (2017). Online Peatland Learning Module. Peatland Action, Scottish Natural Heritage - Accessed at https://www.youtube.com/watch?v=eFSL3vUX5Qw&list=PLSTn6yg6zH__XM-Mw7fKNoGsVYo31B5VH.
Martino, R. (2003). Water, an essential element for life - Accessed at http://www.vatican.va/roman_curia/pontifical_councils/justpeace/documents/rc_pc_justpeace_doc_20030322_kyoto-water_en.html. *Note prepared by the pontifical council for justice and peace*.
Maskell, L., Smart, S., Bullock, J., Thompson, K. and Stevens, C. (2010). Nitrogen deposition causes widespread loss of species richness in British habitats. *Global Change Biology* **16**, 671–679. doi:10.1111/j.1365-2486.2009.02022.x.
Mattson, J., Smith, C., Jones, T. and Gerchakov, S. (1974). Continuous monitoring of dissolved organic matter by UV-visible photometry. *Limnology and Oceanography* **19**, 530–535. doi:10.4319/lo.1974.19.3.0530.
Mayaux, P., de Grandi, G., Rauste, Y., Simard, M. and Saatchi, S. (2002). Large-scale vegetation maps derived from the combined L-band GRFM and C-band CAMP wide area radar mosaics of Central Africa. *International Journal of Remote Sensing* **23**, 1261–1282.
McBride, A., Diack, I., Droy, N., Hamill, B., Jones, P., Schutten, J., Skinner, A. and Street, M. (2011). *The Fen Management Handbook*. Perth.
McDowell, W. (1985). Kinetics and mechanisms of dissolved organic carbon retention in a headwater stream. *Biogeochemistry* **2**, 329–352.
McKenzie, J., Voss, C. and Siegel, D. (2007). Groundwater flow with energy transport and water-ice phase change: Numerical simulations, benchmarks, and application to freezing in peat bogs. *Advances in Water Resources* **30**, 966–983. doi:10.1016/j.advwatres.2006.08.008.
Mcvean, D. (1961). Cladonia Elongata (Jacq .) Hoffm . in the Cairngorms. *The Lichenologist* 94–96.
Met Office (2014a). UK Climate Summaries Annual 2013 - Accessed at http://www.metoffice.gov.uk/climate/uk/summaries/2013/annual.
Met Office (2014b). Winter storms, December 2013 to January 2014 - Accessed at http://www.metoffice.gov.uk/public/weather/climate/.
Met Office (2017a). UK Climate Averages Map - Accessed at http://www.metoffice.gov.uk/public/weather/climate/.
Met Office (2017b). UK Actual and Anomaly Maps - Accessed at http://www.metoffice.gov.uk/climate/uk/summaries/anomacts.
Met Office (2017c). UK Climate Summaries Annual 2016 - Accessed at http://www.metoffice.gov.uk/climate/uk/summaries/2016/annual.
Met Office (2019a). *UKCP18 Factsheet: Snow*.
Met Office (2019b). *UKCP18 Factsheet: Precipitation*.
Meyles, E., Williams, A., Ternan, J., Anderson, J. and Dows, J. (2006). The influence of grazing vegetation, soil properties and stream discharge in a small Dartmoor catchment, southwest England, UK. *Earth Surface Processes and Landforms* **31**, 622–631. doi:10.1002/esp.
Mighall, T., Abrahams, P., Grattan, J., Hayes, D., Timberlake, S. and Forsyth, S. (2002). Geochemical evidence for atmospheric pollution derived from prehistoric copper mining at Copa Hill, Cwmystwyth, mid-Wales, UK. *The Science of the total environment* **292**, 69–80.
Milne, R. and Brown, T. (1997). Carbon in the Vegetation and Soils of Great Britain. *Journal of Environmental Management* **49**, 413–433. doi:10.1006/jema.1995.0118.
Mitchell, B. and McCowan, D. (1986). Performance and population dynamics in relation to management of red deer Cervus elaphus at Glenfeshie, inverness-shire, Scotland. *Biological Conservation* **37**, 237–267. doi:https://doi.org/10.1016/0006-3207(86)90084-4.
Mohr, D., Cohnstaedt, L. and Topp, W. (2005). Wild boar and red deer affect soil nutrients and soil biota in steep oak stands of the Eifel. *Soil Biology and Biochemistry* **37**, 693–700. doi:10.1016/j.soilbio.2004.10.002.

Monbiot, G. (2014). Feral: Rewilding the Land, Sea and Human Life. 336.
Monna, F., Galop, D., Carozza, L., Tual, M., Beyrie, A., Marembert, F., Chateau, C., Dominik, J. and Grousset, F. (2004). Environmental impact of early Basque mining and smelting recorded in a high ash minerogenic peat deposit. *The Science of the total environment* **327**, 197–214. doi:10.1016/j.scitotenv.2004.01.010.
Montanarella, L., Jones, R. and Hiederer, R. (2006). The distribution of peatland in Europe. *Mires and Peat* **1**, 1–10. doi:10.1017/CBO9781107415324.004.
Moody, C., Worrall, F., Evans, C. and Jones, T. (2013). The rate of loss of dissolved organic carbon (DOC) through a catchment. *Journal of Hydrology* **492**, 139–150. doi:10.1016/j.jhydrol.2013.03.016.
Moore, P. and Bellamy, D. (1974). *Peatlands*. Springer-Verlag.
Moore, T. and Knowles, R. (1990). Methane emissions from fen, bog and swamp peatlands in Quebec. *Biogeochemistry* **11**, 45–61. doi:10.1007/BF00000851.
Moors for the Future Partnership (2012). Peatland structure and formation.
Moors for the Future Partnership (2015a). A Strategy for the Restoration of Blanket Bog in England: An Outcomes Approach. 27.
Moors for the Future Partnership (2015b). *Bare Peat Re-vegetation*.
Morison, J. (2012). Afforested peatland restoration. *ClimateXChange* 13.
Morison, J., Vanguelova, E., Broadmeadow, S., Perks, M., Yamulki, S. and Randle, T. (2010). *Understanding the GHG implications of forestry on peat soils in Scotland*.
Mortlock, D. F. (2007). What is soil erosion? - Accessed at http://www.soilerosion.net/.
Murray, I. and Watson, A. (2015). *Place name discoveries on Upper Deeside and the far Highlands*. First. Paragon Publishing, UK.
National River Flow Archive (2017). 8013 - Feshie at Feshie Bridge - Accessed at http://nrfa.ceh.ac.uk/data/station/meanflow/8013. *National River Flow Archive*.
National River Flow Archive (2018). Derived flow statistics - Accessed at http://nrfa.ceh.ac.uk/derived-flow-statistics.
Neal, C. and Hill, S. (1994). Dissolved inorganic and organic carbon in moorland and forest streams: Plynlimon, Mid-Wales. *Journal of Hydrology* **153**, 231–243. doi:10.1016/0022-1694(94)90193-7.
NERC (CEH) (2019). 8013 - Feshie at Feshie Bridge.
Newbigin, M. (1906). The Kingussie district: A geographical study. *Scottish Geographical Magazine* **22**, 285–315. doi:10.1080/14702540608554664.
Newey, S., Dahl, F., Willebrand, T. and Thirgood, S. (2007). Unstable dynamics and population limitation in mountain hares. *Biological Reviews* **82**, 527–549. doi:10.1111/j.1469-185X.2007.00022.x.
Newey, S., Iason, G. and Raynor, R. (2008). The conservation status and management of mountain hares. *Scottish Natural Heritage Commissioned Report* **No. 287**, 39.
Nguyen, C. (2009). Agronomy for sustainable development. In *Agronomy for sustainable development*, pp. 97–123. Springer Netherlands doi:10.1007/978-90-481-2666-8_9.
Nilsen, E., Milner-Gulland, E., Schofield, L., Mysterud, A., Stenseth, N. and Coulson, T. (2007). Wolf reintroduction to Scotland: public attitudes and consequences for red deer management. *Proceedings Of The Royal Society B* **274**, 995–1002. doi:10.1098/rspb.2006.0369.
Nilsson, C. and Renöfält, B. (2008). Linking Flow Regime and Water Quality in Rivers : a Challenge to Adaptive Catchment Management. *Ecology and Society* **13**, 18.
Noble, A., Palmer, S., Glaves, D., Crowle, A. and Holden, J. (2019). Peatland vegetation change and establishment of re-introduced Sphagnum moss after prescribed burning. *Biodiversity and Conservation* **28**, 939–952. doi:10.1007/s10531-019-01703-0.
Nungesser, M. K. (2003). Modelling microtopography in boreal peatlands: hummocks and hollows. *Ecological Modelling* **165**, 175–207. doi:10.1016/S0304-3800(03)00067-X.
O'Donnell, G., Ewen, J. and O'Connell, P. (2011). Sensitivity maps for impacts of land management on an extreme flood in the Hodder catchment, UK. *Physics and Chemistry of the Earth* **36**, 630–637. doi:10.1016/j.pce.2011.06.005.
O Dochartaigh, B., MacDonald, A., Fitzsimons, V. and Ward, R. (2015). *Scotland's aquifers and groundwater bodies*. Nottingham, UK doi:(OR/15/028).
Odgaard, B. (1992). The fire history of Danish heathland areas as reflected by pollen and charred particles in lake sediments. *The Holocene* **2**, 218–226. doi:10.1177/095968369200200303.
Open Government Licence V3.0 (2018). legilsation.gov.uk.
Orr, H. and Carling, P. (2006). Hydro-climatic and land use changes in the river lune catchment, North West England, implications for catchment management. *River Research and Applications* **22**, 239–255. doi:10.1002/rra.908.
Osterkamp, T. and Burn, C. (2003). Permafrost. *Permafrost* 1717–1729. doi:10.1006/rwos.2001.0384.

Ostle, N., Levy, P., Evans, C. and Smith, P. (2009). UK land use and soil carbon sequestration. *Land Use Policy* **26**, 274–283. doi:10.1016/j.landusepol.2009.08.006.

Owens, I., Burke, T. and Thompson, D. (1994). Extraordinary Sex Roles in the Eurasian Dotterel : Female Mating Arenas , Female-Female Competition , and Female Mate Choice. *The American Naturalist* **144**, 76–100.

Owings, C., Jacobs, D., Shields, J., Saunders, M. and Jenkins, M. (2017). Individual and interactive effects of white-tailed deer and an exotic shrub on artificial and natural regeneration in mixed hardwood forests. *AoB Plants* **9**,. doi:10.1093/aobpla/plx024.

Page, S., Hosciło, A., Wösten, H., Jauhiainen, J., Silvius, M., Rieley, J., Ritzema, H., Tansey, K., Graham, L., Vasander, H. and Limin, S. (2009). Restoration Ecology of Lowland Tropical Peatlands in Southeast Asia: Current Knowledge and Future Research Directions. *Ecosystems* **12**, 888–905. doi:10.1007/s10021-008-9216-2.

Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M. and Stringer, L. (2008). *Assessment on Peatland, Biodiversity and Climate Change*. Global Environment Centre, Kuala Lumpur & Wetlands International, Wageningen doi:10.1017/CBO9781107415324.004.

Parkyn, L., Stoneman, R. and Ingram, H. (1997). *Conserving Peatlands*. CAB International, Wallingford, UK.

Pastor, J., Solin, J., Bridgham, S., Updegraff, K., Harth, C., Weishampel, P. and Dewey, B. (2003). Global warming and the export of dissolved organic carbon from boreal peatlands. *Oikos* **100**, 380–386. doi:10.1034/j.1600-0706.2003.11774.x.

Patterson, G., Nelson, D., Robertson, P. and Tullis, J. (2014). Scotland's Native Woodlands: Results from the Native Woodland Survey of Scotland. *Forestry Commission Scotland* 1–104.

Pegau, R. (1970). Effect of Reindeer Trampling and Grazing on Lichens. *Journal of Range Management* **23**, 95–97.

Pellerin, S., Huot, J. and Côté, S. (2006). Long-term effects of deer browsing and trampling on the vegetation of peatlands. *Biological Conservation* **128**, 316–326. doi:10.1016/j.biocon.2005.09.039.

Peteranna, M. and Fraser, L. (2010). Archaeological Walk-over Survey and Mitigation for Cable Undergrounding Project. *Glen Feshie Final Report* **HAS100509**, 1–32.

Pickard, A., Heal, K., McLeod, A. and Dinsmore, K. (2017). Temporal changes in photoreactivity of dissolved organic carbon and implications for aquatic carbon fluxes from peatlands. *Biogeosciences* **14**, 1793–1809. doi:10.5194/bg-14-1793-2017.

Plantlife (2010). Upland: The issues - Accessed at http://www.plantlife.org.uk/wild_plants/habitats/upland.

Pokrovsky, O., Viers, J., Shirokova, L., Shevchenko, V., Filipov, A. and Dupré, B. (2010). Dissolved, suspended, and colloidal fluxes of organic carbon, major and trace elements in the Severnaya Dvina River and its tributary. *Chemical Geology* **273**, 136–149. doi:10.1016/j.chemgeo.2010.02.018.

Post, F. and Dreibelbis, F. (1942). Some influence of frost penetration and microclimate on the water relationships of woodland, pasture and cultivated soils. *Soil Sci. Soc. Proc.* **7**, 95–104.

Pressland, D. (2012). Brocket - Accessed at http://www.wildlifeonline.me.uk/questions_answers_deer.html. http://www.wildlifeonline.me.uk/questions_answers_.

Priest, S. (2012). Peatland Acidification and Understanding pH. *Orono Bog Boardwalk Factsheet* 4.

Proctor, M. (2003). Malham Tarn Moss: The surface-water chemistry of an ombrotrophic bog. *Field Studies* **10**, 553–578.

Puhr, C., Donoghue, D., Stephen, A., Tervet, D. and Sinclair, C. (2000). Regional Patterns of Streamwater Acidity and Catchment Afforestation in Galloway, SW Scotland. *Water, Air, and Soil Pollution* **120**, 47–70.

Putman, R. (2012). Scoping the economic benefits and costs of wild deer and their management in Scotland. *Scottish Natural Heritage Commissioned Report* **No. 526**, 40.

Putman, R. and Langbein, J. (2003). *The Deer Manager's Companion*. Swan Hill Press.

Putman, J. and Staines, B. (2004). Supplementary winter feeding of wild red deer. *Mammal Review* **34**, 285–306. doi:10.1111/j.1365-2907.2004.00044.x.

Putman, R., Duncan, P. and Scott, R. (2005). Demographic changes in a Scottish red deer population (Cervus elaphus L.) in response to sustained and heavy culling: An analysis of trends in deer populations of Creag Meagaidh National Nature Reserve 1986-2001. *Forest Ecology and Management* **206**, 263–281. doi:10.1016/j.foreco.2004.11.006.

Qassim, S., Dixon, S., Rowson, J., Worrall, F., Evans, M. and Bonn, A. (2014). A 5-year study of the impact of peatland revegetation upon DOC concentrations. *Journal of Hydrology* **519**, 3578–3590. doi:10.1016/j.jhydrol.2014.11.014.

Querner, E., Mioduszewski, W., Povilaitis, A. and Slesicka, A. (2010). Modelling peatland

hydrology: Three cases from Northern Europe. *Polish Journal of Environmental Studies* **19**, 149–159.
Radley, J. (1962). Peat erosion on the high moors of Derbyshire and west Yorkshire. *East Midland Geographer* **3**, 40–50.
Rae, S. (1994). Individual dispersion and productivity of ptarmigan in relation to their selection of food and cover. *University of Aberdeen, Faculty of Science* 156.
Ramesh-Reddy, K. and DeLaune, R. (2008). *Biochemistry of Wetlands: Science and Application*. 1st ed. (ed. Francis, T. and) CRC Press, USA.
Rao, S. (2017). Effect of reducing red deer Cervus elaphus density on browsing impact and growth of Scots pine Pinus sylvestris seedlings in semi-natural woodland in the Cairngorms, UK. *Conservation Evidence* **14**, 22–26.
Ratcliffe, D. (1977a). *A Nature Conservation Review*. Cambridge University Press, Cambridge.
Ratcliffe, D. (1977b). Uplands and Birds—an Outline. *Bird Study* **24**, 140–158. doi:10.1080/00063657709476550.
Ratcliffe, D. (1986). Selection of important areas for wildlife conservation in Great Britain: the Nature Conservancy Council's approach. In Usher, M.B. (ed.). In *Wildlife conservation evaluation*, pp. 135–139. Chapman and Hall, London.
Ratcliffe, D. (1990). *Bird life of mountain and upland*. Cambridge University Press, Cambridge.
Ratcliffe, D. and Oswald, P. (1988). The Flow Country. Nature Conservancy Council, Peterborough, UK.
Ratcliffe, J., Payne, R., Sloan, T., Smith, B., Waldron, S., Mauquoy, D., Newton, A., Anderson, A., Henderson, A. and Andersen, R. (2018). Holocene carbon accumulation in the peatlands of northern Scotland. *Mires and Peat* **23**, 1–30. doi:10.19189/MaP.2018.OMB.347.
Raynor, R. (2017). UK's white mountain hares at risk from predators due to worst snowfall in 10 years - Accessed at http://www.telegraph.co.uk/news/2017/02/02/uks-white-mountain-hares-risk-predators-due-worst-snowfall-10/.
Rebsdorf, A., Thyssen, N. and Erlandsen, M. (1991). Regional and temporal variation in pH, alkalinity and carbon dioxide in Danish streams, related to soil type and land use. *Freshwater Biology* **25**, 419–435. doi:10.1111/j.1365-2427.1991.tb01386.x.
Reed, M. (2017). Peatland Tipping Points - Accessed at http://www.peatlandtippingpoints.com/.
Reed, M., Bonn, A., Evans, C., Glenk, K. and Hansjürgens, B. (2014). Assessing and valuing peatland ecosystem services for sustainable management. *Ecosystem Services* **9**, 1–4. doi:10.1016/j.ecoser.2014.04.007.
Rennie, S., Adamson, J., Anderson, R., Andrews, C., Bater, J., Bayfield, N., Beaton, K., Beaumont, D., Benham, S., Bowmaker, V., Britt, C., Brooker, R., Brooks, D., Brunt, J., Common, G., Cooper, R., Corbett, S., Critchley, N., Dennis, P., Dick, J., Dodd, B., Dodd, N., Donovan, N., Easter, J., Eaton, E., Flexen, M., Gardiner, A., Hamilton, D., Hargreaves, P., Hatton-Ellis, M., Howe, M., Kahl, J., Lane, M., Langan, S., Lloyd, D., McCarney, B., McElarney, Y., McKenna, C., McMillan, S., Milne, F., Milne, L., Morecroft, M., Murphy, M., Nelson, A., Nicholson, H., Pallett, D., Parry, D., Pearce, I., Pozsgai, G., Rose, R., Schafer, S., Scott, T., Sherrin, L., Shortall, C., Smith, R., Smith, P., Tait, R., Taylor, C., Taylor, M., Thurlow, M., Turner, A., Tyson, K., Watson, H., Whittaker, M., Wilkinson, M. and Wood, C. (2017). UK Environmental Change Network (ECN) meteorology data: 1991-2015.
Riise, G., Van Hees, P., Lundström, U. and Tau Strand, L. (2000). Mobility of different size fractions of organic carbon, Al, Fe, Mn and Si in podzols. *Geoderma* **94**, 237–247. doi:10.1016/S0016-7061(99)00044-0.
Ritchie, J. (2015). *The Influence of Man on Animal Life in Scotland. A Study in Faunal Evolution.* First Publ. Cambridge University Press, United Kingdom.
Rodríguez-Iturbe, I. and Porporato, A. (2004). *Ecohydrology of water-controlled ecosystems. Soil moisture and plant dynamics.* Cambridge University Press, Cambridge.
Romaní, A. (1997). Heterotrophic and autotrophic metabolism in Mediterranean streams. *University of Barcelona, Department of Biology* 87.
Roos, S., Donald, C., Dugan, D., Hancock, M., O'Hara, D., Stephen, L. and Grant, M. (2016). Habitat associations of young Black Grouse Tetrao tetrix broods. *Bird Study* **63**,. doi:http://dx.doi.org/10.1080/00063657.2016.1141167.
Royal Scottish Geographical Society (2015). Dick Balharry's Vision for Land Use in Scotland, Accessed at http://rsgs.org/dickbalharrysvisionforlanduseinscotland/.
RSPB Scotland (2009). *The Peatlands of Scotland The urgent need for restoration and conservation*.
Rydin, H. and Jeglum, J. (2013). *The Biology of Peatlands*. Second Edi. Oxford University Press, Oxford.
S::can (2016). s:can Global Calibrations - Accessed at http://www.s-can.at/text.php?kat=11&id=59&langcode.

Sakai, M., Natuhara, Y., Imanishi, A., Imai, K. and Kato, M. (2011). Indirect effects of excessive deer browsing through understory vegetation on stream insect assemblages. *Population Ecology* **54**, 65–74. doi:10.1007/s10144-011-0278-1.

Schellekens, J. and Buurman, P. (2011). n-Alkane distributions as palaeoclimatic proxies in ombrotrophic peat: The role of decomposition and dominant vegetation. *Geoderma* **164**, 112–121. doi:10.1016/j.geoderma.2011.05.012.

Scotland's Environment (2014). Mountains and uplands.

Scotland's Environment (2017). National Map of Scotland.

Scott, M. (2016a). *Mountain Flowers*. First. Bloomsbury Publishing Plc, London.

Scott, F. (2016b). Investigating the factors affecting arctic-alpine vegetation abundance and diversity on the Mòine Mhór , Cairngorms National Park. *University of Dundee, Geography,* 88.

Scott, M., Jones, M., Woof, C. and Tipping, E. (1998). Concentrations and fluxes of dissolved organic carbon in drainage water from an upland peat system. *Environment International* **24**, 537–546. doi:https://doi.org/10.1016/S0160-4120(98)00043-9.

Scottish Environment Protection Agency (2015). *Spey Bay (Potentially Vulnerable Area 05/04) - Accessed at http://apps.sepa.org.uk/frmstrategies/pdf/pva/PVA_05_04_Full.pdf*.

Scottish Environment Protection Agency (2016). SEPA Water Level Data - Accessed at http://apps.sepa.org.uk/waterlevels/default.aspx?sd=t&lc=234217.

Scottish Environment Protection Agency (2017). Rainfall Information - Accessed at http://apps.sepa.org.uk/rainfall/RainfallInformation.

Scottish Government (2018). *Climate Change Plan: The Third Report on Proposals and Policies 2018-2032*. doi:9781788516518.

Scottish Natural Heritage (2001). *Boglands. Scotland's Living Landscapes - Accessed at http://www.snh.org.uk/pdfs/publications/livinglandscapes/boglands.pdf*.

Scottish Natural Heritage (2011). *Peat erosion and the management of peatland habitats. Scottish Natural Heritage Commissioned Report No. 410*.

Scottish Natural Heritage (2013). Deer Population Management - Accessed at http://www.snh.gov.uk/land-and-sea/managing-wildlife/managing-deer/understanding/deer-population-management/.

Scottish Natural Heritage (2015). *Scotland's National Peatland Plan: Working for our future*.

Scottish Natural Heritage (2016a). *Deer Management in Scotland : Report to the Scottish Government from Scottish Natural Heritage 2016*.

Scottish Natural Heritage (2016b). Action for Peatlands - Accessed at http://www.snh.gov.uk/climate-change/taking-action/carbon-management/peatland-action/.

Scottish Natural Heritage (2016c). Natural Spaces - Accessed at https://gateway.snh.gov.uk/natural-spaces/index.jsp.

Scottish Natural Heritage (2016d). *Carbon-rich soils , deep peat and priority peatland habitat mapping - Accessed at http://www.snh.gov.uk/docs/A2010617.pdf*.

Scottish Natural Heritage (2016e). Sitelink: Site Details for Cairngorms - Accessed at http://gateway.snh.gov.uk/sitelink/siteinfo.jsp?pa_code=8217.

Scottish Natural Heritage (2017a). Peatland ACTION Project 2017/18 - Accessed at http://www.snh.gov.uk/climate-change/taking-action/carbon-management/peatland-action/information-for-applicants/.

Scottish Natural Heritage (2017b). Site Details for Cairngorms - Accessed at http://gateway.snh.gov.uk/sitelink/siteinfo.jsp?pa_code=288#features. *SSSI Citation* 6.

Scottish Natural Heritage (2019a). *Peatland ACTION Guidance for land managers: Dam Installation techniques – Peat and Plastic dams*.

Scottish Natural Heritage (2019b). Peatland ACTION Funding.

Scottish Renewables et al. (2010). *Good practice during windfarm construction*.

Scottish Water (2015). Water Quality Standards - Accessed at http://www.scottishwater.co.uk/you-and-your-home/your-home/customer-factsheets/2-water-quality-standards. *Water Quality Standards Explained* 1–4.

Scottish Wildlife Trust (1997). *Conserving Bogs: The Management Handbook*. Stationery Office Books.

Scrope, W. (1839). *The art of deerstalking*. London, J. Murray.

Searcy, J. (1969). *Flow-Duration Curves. Manual of Hydrology: Part 2. Low-Flow Techniques*. doi:10.1002/047147844X.sw321.

Seibel, B. (2014). Understanding Total Organic Carbon (TOC) and Why it should be Measured - Accessed at http://blog.teledynetekmar.com/blog/bid/392322/Understanding-Total-Organic-Carbon-TOC-and-Why-it-should-be-Measured.

SeptemberWoman (2012). Deutsch: Dubringer Moor bei Wittichenau - Accessed at https://commons.wikimedia.org/wiki/File:Dubringer_Moor_2.JPG#file.

Seters, T. E. Van and Price, J. S. (2002). Towards a conceptual model of hydrological change on an abandoned cutover bog , Quebec. *Hydrological Processes* **16**, 1965–1981. doi:10.1002/hyp.396.

Shannon, R. and White, J. (1996). The effects of spatial and temporal variations in acetate and sulfate on methane cycling in two Michigan peatlands. *Limnology and Oceanography* **41**, 435–443. doi:10.4319/lo.1996.41.3.0435.

Sheffield Hallam University Gas Chromatography - Accessed at https://teaching.shu.ac.uk/hwb/chemistry/tutorials/chrom/gaschrm.htm.

Sheppard, L., Leith, I., Leeson, S., Van Dijk, N., Field, C. and Levy, P. (2013). Fate of N in a peatland, Whim bog: Immobilisation in the vegetation and peat, leakage into pore water and losses as N2O depend on the form of N. *Biogeosciences* **10**, 149–160. doi:10.5194/bg-10-149-2013.

Shimadzu Corportation (2017). TOC Analyzers - Accessed at http://www.shimadzu.com/an/toc/lab/toc-l4.html.

Shotyk, W. (1998). History of Atmospheric Lead Deposition Since 12,370 14C yr BP from a Peat Bog, Jura Mountains, Switzerland. *Science* **281**, 1635–1640. doi:10.1126/science.281.5383.1635.

Shotyk, W., Weiss, D., Kramers, J. D. and Frei, R. (2001). Geochemistry of the peat bog at Etang de la Grue ` re , Jura Mountains , Switzerland , and its record of atmospheric Pb and lithogenic trace metals (Sc , Ti , Y , Zr , and REE) since 12 , 370 C yr BP. *Geochimica et Cosmochimica Acta* **65**, 2337–2360.

Siegel, D. (1983). Ground Water and the Evolution of Patterned Mires, Glacial Lake Agassiz Peatlands, Northern Minnesota. *Journal of Ecology* **71**, 913–921.

Siegel, D. (1988). The Recharge-Discharge Function of Wetlands Near Juneau, Alaska Part II. Geochemical Investigations. *Ground Water* **26**, 580–586.

Siegel, D. and Glaser, P. (2006). The Hydrology of Peatlands. In *Boreal Peatland Ecosystems* (ed. Wieder, R.) and Vitt, D.), pp. 289–311. Springer Berlin Heidelberg, Berlin, Heidelberg doi:10.1007/978-3-540-31913-9_13.

Silvola, J., Alm, J., Ahlholm, U., Nykänen, H. and Martikainen, P. (1996a). The contribution of plant roots to CO2 fluxes from organic soils. *Biology and Fertility of Soils* **23**, 126–131. doi:10.1007/s003740050149.

Silvola, J., Alm, J., Ahlholm, U., Nykanen, H. and Martikainen, P. (1996b). CO2 fluxes from peat in boreal mires under varying temperature and moisture conditions. *Journal of Ecology* **84**, 219–228.

Sing, L., Ray, D. and Watts, K. (2015). Ecosystem services and forest management. *Research Note, Forestry Commission* 1–10.

Smart, P., Finlayson, B., Rylands, W. and Ball, C. (1976). The relation of fluorescence to dissolved organic carbon in surface waters. *Water Research* **10**, 805–811. doi:https://doi.org/10.1016/0043-1354(76)90100-7.

Smart, S., Henrys, P., Scott, W., Hall, J., Evans, C., Crowe, A., Rowe, E., Dragosits, U., Page, T., Whyatt, J., Sowerby, A. and Clark, J. (2010). Impacts of pollution and climate change on ombrotrophic Sphagnum species in the UK: analysis of uncertainties in two empirical niche models. *Climate Research* **45**, 163–177. doi:10.3354/cr00969.

Smerdon, B. and Mendoza, C. (2010). Hysteretic freezing characteristics of riparian peatlands in the Western Boreal forest of Canada. *Hydrological Processes* **24**, 1027–1038. doi:10.1002/hyp.7544.

Smith, R. (1872). *Air and Rain: the Beginnings of a Chemical Climatology - Accessed at https://archive.org/details/airrainbeginning00smitiala*. London : Longmans, Green, and co.

Smith, R. (1994). Snow buntings breeding in the Cairngorms: population dynamics and the influence of recreation. *Scottish Natural Heritage Review* **No. 1**, 69.

Smith, P., Chapman, S., Scott, W., Black, H., Wattenbach, M., Milne, R., Campbell, C., Lilly, A., Ostle, N., Levy, P., Lumsdon, D., Millard, P., Towers, W., Zaehle, S. and Smith, J. (2007a). Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978-2003. *Global Change Biology* **13**, 2605–2609. doi:10.1111/j.1365-2486.2007.01458.x.

Smith, P., Smith, J., Fynn, H., Killham, K., Rangel-Castro, I., Foereid, B., Aitkenhead, M., Chapman, S., Towers, W. and Bell, J. (2007b). *ECOSSE - Estimating Carbon in Organic Soils Sequestration and Emission*.

SNH (2017). *Upland Flushes and Swamps (UK BAP Priority Habitat)*.

Soil Survey of Scotland Staff (1984). Organisation and methods of the 1:250 000 soil survey of Scotland. Handbook 8. *The Macaulay Institute for Soil Research*.

Soulsby, C., Helliwell, R., Ferrier, R., Jenkins, A. and Harriman, R. (1997). Seasonal snowpack influence on the hydrology of a sub-arctic catchment in Scotland. *Journal of Hydrology* **192**, 17–32. doi:10.1016/S0022-1694(96)03123-X.

Soulsby, C., Malcolm, R., Gibbins, C. and Dilks, C. (2001). Seasonality, water quality trends and

biological responses in four streams in the Cairngorm Mountains, Scotland. *Hydrology and Earth System Sciences* **5**, 433–450. doi:10.5194/hess-5-433-2001.
Soulsby, C., Gibbins, C., Wade, A., Smart, R. and Helliwell, R. (2002). Water quality in the Scottish uplands: A hydrological perspective on catchment hydrochemistry. *Science of the Total Environment* **294**, 73–94. doi:10.1016/S0048-9697(02)00057-8.
Soulsby, C., Rodgers, P., Petry, J., Hannah, D., Malcolm, I. and Dunn, S. (2004). Using tracers to upscale flow path understanding in mesoscale mountainous catchments: Two examples from Scotland. *Journal of Hydrology* **291**, 174–196. doi:10.1016/j.jhydrol.2003.12.042.
Soulsby, C., Tetzlaff, D., Rodgers, P., Dunn, S. and Waldron, S. (2006). Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: An initial evaluation. *Journal of Hydrology* **5**, 1–25. doi:10.1016/j.jhydrol.2005.10.024.
Spaven, D. (2016). *Conserving Natural Capital: The National Trust for Scotland's peatlands*.
Stähli, M. and Stadler, D. (1997). Measurement of water and solute dynamics in freezing soil columns with time domain reflectometry. *Journal of Hydrology* **195**, 352–369. doi:10.1016/S0022-1694(96)03227-1.
Strack, M. (2008). *Peatlands and Climate Change*. International Peat Society, Finland doi:10.5194/bg-7-1505-2010.
Stromayer, K. and Warren, R. (1997). Are Overabundant Deer Herds in the Eastern United States Creating Alternate Stable States in Forest Plant Communities? *Wildlife Society Bulletin (1973-2006)* **25**, 227–234.
Stroud, A., Reed, T., Pienkowski, M. and Lindsay, R. (1987). Birds, Bogs and Forestry. *Nature Conservancy Council*.
Suburban Whitetail Mangement of Northern Virginia (2017). Deer Facts, Accessed at http://www.deerdamage.org/page/deer-facts.
Takatsuki, S. (2009). Effects of sika deer on vegetation in Japan: A review. *Biological Conservation* **142**, 1922–1929. doi:10.1016/j.biocon.2009.02.011.
Tallis, J. (1964). Studies on Southern Pennine Peats : II . The Pattern of Erosion. *Journal of Ecology* **52**, 333–344.
Tallis, J. (1965). Studies on Southern Pennine Peats : IV . Evidence of Recent Erosion. *Journal of Ecology* **53**, 509–520.
Tallis, J. (1973). Studies on Southern Pennine Peats: V. Direct Observations on Peat Erosion and Peat Hydrology at Featherbed Moss, Derbyshire. *Journal of Ecology* **61**, 1–22. doi:10.1111/j.1365-2664.2005.01116.x.
Tallis, J. H. (1985). Mass Movement and Erosion of a Southern Pennine Blanket Peat. *Journal of Ecology* **73**, 283–315.
Tallis, J. H. (1987). Fire and Flood at Holme Moss : Erosion Processes in an Upland Blanket Mire. *Journal of Ecology* **75**, 1099–1129.
Tallis, J. (1991). Forest and Moorland in the South Pennine Uplands in the Mid-Flandrian Period .: III . The Spread of Moorland--Local , Regional and National. *Journal of Ecology* **79**, 401–415.
Tallis, J. (1994). Pool-and-hummock patterning in a southern Pennine blanket mire. II. The formation and erosion of the pool system. *Journal of Ecology* **82**, 789–803.
Tallis, J. H. (1997). The pollen record of Empetrum nigrum in southern Pennine peats : implications for erosion and climate change. *Journal of Ecology* **85**, 455–465.
Tallis, J. (1998). Growth and degradation of British and Irish blanket mires. *Environmental Reviews* **6**, 81–122. doi:10.1139/a98-006.
Tallis, J. and Switsur, V. (1973). Studies on Southern Pennine Peats: VI. A Radiocarbon-Dated Pollen Diagram from Featherbed Moss, Derbyshire. *The Journal of Ecology* **61**, 743–751.
Taylor, E. (2014). The Impact of Fire on Blanket Bogs : Implications for Vegetation and the Carbon Cycle. *The University of Edinburgh* 251.
Taylor, M. and Kitchener, A. (2002). *Scotland's Beginnings: Scotland Through Time (Our Land)*. NMSE - Publishing Ltd.
The AONB Partnership (2019). Restoration.
The James Hutton Institute (2013). National Soil Map of Scotland - Accessed at http://map.environment.gov.scot/Soil_maps/?layer=1.
The Peatlands Parternership (2018). The Flow Country - Accessed at http://theflowcountry.org.uk/.
The Reindeer Company (1993). Reindeer (Rangifer tarandus). 1–16.
The Royal Society for the Protection of Birds (2013). 12 Point Red Deer Stag - Accessed at https://ww2.rspb.org.uk/community/placestovisit/leightonmoss/m/leightonmoss-mediagallery/766685.aspx.
The Scottish Government (2011). The Muirburn Code. 27.
The Scottish Government (2013). *Parliamentary Question S4W-12042 - Accessed at http://www.parliament.scot/S4_ChamberDesk/WA20130130.pdf*.

The Scottish Government (2015). Climate change action heats up - Accessed at http://news.gov.scot/news/climate-change-action-heats-up.

The Scottish Government (2018). Carbon Calculator Tool v1.5.1. Revised 2011.

Thomas, J. (1997). The role of dissolved organic matter, particularly free amino acids and humic substances, in freshwater ecosystems. *Freshwater Biology* **38**, 1–36. doi:10.1046/j.1365-2427.1997.00206.x.

Thompson, D. and Brown, A. (1992). Biodiversity in montane Britain: habitat variation, vegetation diversity and some objectives for conservation. *Biodiversity and Conservation* **1**, 179–208. doi:10.1007/BF00695915.

Thompson, D., Watson, A., Rae, S. and Boobyer, G. (1996). Recent changes in breeding bird populations in the Cairngorms. *Botanical Journal of Scotland* **48**, 99–110. doi:10.1080/03746609609480377.

Thurman, E. and Malcolm, R. (1981). Preparative isolation of aquatic humic substances. *Environmental Science and technology* **15**, 463–466.

Thurman, E. and Malcolm, R. (1983). Humic substances in groundwater. *Abstracts of Papers of the American Chemical Society* **186**, 89.

Tipping, R. (1994). The form and fate of Scotland's woodlands. *Proceedings of the Society of Antiquaries of Scotland* **124**, 1–54.

Tipping, E., Henrys, P., Maskell, L. and Smart, S. (2013). Nitrogen deposition effects on plant species diversity; Threshold loads from field data. *Environmental Pollution* **179**, 218–223. doi:10.1016/j.envpol.2013.04.008.

Tomlinson, R. (1982). Seven Bog Slides in the Slieve-an-Orra Hills , County Antrim. *Journal of Earth Sciences* **5**, 1–9.

Tranvik, L., Downing, J., Cotner, J., Loiselle, S., Striegl, R., Ballatore, T., Dillon, P., Finlay, K., Fortino, K., Knoll, L., Kortelainen, P., Kutser, T., Larsen, S., Laurion, I., Leech, D., McCallister, L., McKnight, D., Melack, J., Overholt, E., Porter, J., Prairie, Y., Renwick, W., Roland, F., Sherman, B., Schindler, D., Sobek, S., Tremblay, A., Vanni, M., Verschoor, A., Von Wachenfeldt, E. and Weyhenmeyer, G. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography* **54**, 2298–2314. doi:10.4319/lo.2009.54.6_part_2.2298.

Trinder, C., Johnson, D. and Artz, R. (2009). Litter type, but not plant cover, regulates initial litter decomposition and fungal community structure in a recolonising cutover peatland. *Soil Biology and Biochemistry* **41**, 651–655. doi:10.1016/j.soilbio.2008.12.006.

Tunaley, C., Tetzlaff, D. and Soulsby, C. (2017). Scaling effects of riparian peatlands on stable isotopes in runoff and DOC mobilisation. *Journal of Hydrology* **549**, 220–235. doi:10.1016/j.jhydrol.2017.03.056.

Tunaley, C., Tetzlaff, D., Wang, H. and Soulsby, C. (2018). Spatio-temporal diel DOC cycles in a wet, low energy, northern catchment: Highlighting and questioning the sub-daily rhythms of catchment functioning. *Journal of Hydrology* **563**, 962–974. doi:10.1016/j.jhydrol.2018.06.056.

Turner, N. (1757). An Essay on Draining and Improving Peat Bogs; in Which Their Nature and Properties Are Fully Considered.p. Baldwin and Pew, London.

Turner, E., Worrall, F. and Burt, T. (2013). The effect of drain blocking on the dissolved organic carbon (DOC) budget of an upland peat catchment in the UK. *Journal of Hydrology* **479**, 169–179. doi:10.1016/j.jhydrol.2012.11.059.

Turunen, J., Tomppo, E., Tolonen, K. and Reinikainen, A. (2002). Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions. *The Holocene* **12**, 69–80. doi:10.1191/0959683602hl522rp.

UK Marine SACs Project (2001). Exposure to water movement - Accessed at http://www.ukmarinesac.org.uk/communities/circalittoral/cf2_3.htm.

UK Technical Advisory Group (2008). *UK Environmental Standards and Conditions (Phase 1) Final Report*.

United States Department of Agriculture (2017). Types of fens - Accessed at https://www.fs.fed.us/wildflowers/beauty/California_Fens/types.shtml.

Updegraff, K., Bridgham, S., Pastor, J., Weishampel, P. and Harth, C. (2001). Response of CO2 and CH4 emissions from peatlands to warming and water table manipulation. *Ecological Applications* **11**, 311–326.

Urban, N., Bayley, S. and Eisenreich, S. (1989). Export of dissolved organic-carbon and acidity from peatlands. *Water Resources Research* **25**, 1619–1628. doi:10.1029/WR025i007p01619.

UT-Battelle for the Department of Energy (2018). SPRUCE Facilities Orientation.

Utsi, M. (1957). The Future of Reindeer in Scotland. *Oryx* **4**, 40–42. doi:10.1017/S0030605300039223.

Vaisala (2019). *GMP343 Carbon Dioxide Probe*.

van Breemen, N. (1995). How Sphagnum bogs down other plants. *Trends in Ecology and Evolution* **10**, 270–275. doi:http://dx.doi.org/10.1016/0169-5347(95)90007-1.

Vannote, R., Minshall, W., Cummins, K., Sedell, J. and Cushing, C. (1980). The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences* **37**, 130–137. doi:10.1139/f80-017.

Verhoeven, J. T. ., Beltman, B., Bobbink, R. and Whigham, D. (2006). *Wetlands and Natural Resource Management*. Ecological. (ed. Czeschlik, D.) Springer-Verlag Berlin Heidelberg, New York.

Waddington, J. and Price, J. (2000). Effect of Peatland Drainage, Harvesting, and Restoration on Atmospheric Water and Carbon Exchange. *Physical Geography* **21**, 433–451. doi:10.1080/02723646.2000.10642719.

Waddington, J. M. and Roulet, N. T. (1997). Groundwater flow and dissolved carbon movement in a boreal peatland. *Journal of Hydrology* **191**, 122–138. doi:10.1016/S0022-1694(96)03075-2.

Waddington, J., Morris, P., Kettridge, N., Granath, G., Thompson, D. and Moore, P. (2015). Hydrological feedbacks in northern peatlands. *Ecohydrology* **8**, 113–127. doi:10.1002/eco.1493.

Waldron, S., Flowers, H., Arlaud, C., Bryant, C. and McFarlane, S. (2009). The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance, a stoichiometric perspective. *Biogeosciences* **6**, 363–374. doi:10.5194/bg-6-363-2009.

Walker, T., Garnett, M., Ward, S., Oakley, S., Bardgett, R. and Ostle, N. (2016). Vascular plants promote ancient peatland carbon loss with climate warming. *Global Change Biology* **22**, 1880–1889. doi:10.1111/gcb.13213.

Wallin, M., Buffam, I., Öquist, M., Laudon, H. and Bishop, K. (2010). Temporal and spatial variability of dissolved inorganic carbon in a boreal stream network: Concentrations and downstream fluxes. *Journal of Geophysical Research* **115**, 1–12. doi:10.1029/2009jg001100.

Wang, J., Song, C., Hou, A., Miao, Y., Yang, G. and Zhang, J. (2014). Effects of freezing–thawing cycle on peatland active organic carbon fractions and enzyme activities in the Da Xing'anling Mountains, Northeast China. *Environmental Earth Sciences* **72**, 1853–1860.

Warburton, J. (2003). Wind-splash erosion of bare peat on UK upland moorlands. *Catena* **52**, 191–207. doi:10.1016/S0341-8162(03)00014-6.

Warburton, J., Higgitt, D. and Mills, A. (2003). Anatomy of Pennine peat slide, northern England. *Earth Surface Processes and Landforms* **28**, 457–473. doi:10.1002/esp.452.

Ward, S., Bardgett, R., McNamara, N., Adamson, J. and Ostle, N. (2007). Long-term consequences of grazing and burning on northern peatland carbon dynamics. *Ecosystems* **10**, 1069–1083. doi:10.1007/s10021-007-9080-5.

Warren, C. (2000). "Birds, bogs and forestry" revisited: The significance of the flow country controversy. *Scottish Geographical Journal* **116**, 315–337. doi:10.1080/00369220018737103.

Warren, C. (2009). *Managing Scotland's environment*. Second Edi. Edinburgh University Press, Edinburgh.

Warren, R. (2011). Deer overabundance in the USA: recent advances in population control. *Animal Production Science* **51**, 259–266. doi:https://doi.org/10.1071/AN10214.

Watson, A. (1963). The Effect of Climate on the Colour Changes of Mountain Hares in Scotland. *Proceedings of the Zoological Society of London* **141**, 823–835. doi:10.1111/j.1469-7998.1963.tb01629.x.

Watson, A., Hewson, R., Jenkins, D. and Parr, R. (1973). Population densities of mountain hares compared with red grouse on Scottish moors. *Okios* **24**, 225–230.

Watt, A. S. and Jones, E. W. (1948). The Ecology of the Cairngorms. Part 1. The Environment and the Altitudinal Zonation of the Vegetation. *Journal of Ecology* **36**, 283–304.

Watts, C., Naden, P., Machell, J. and Banks, J. (2001). Long term variation in water colour from Yorkshire catchments. *Science of the Total Environment* **278**, 57–72. doi:10.1016/S0048-9697(00)00888-3.

Welsch, D., Smart, D., Boyer, J., Minkin, P., Smith, H. and McCandless, T. (1995). *Forested Wetlands Functions, Benefits and the Use of Best Management Practices*. U.S. Department of Agriculture.

Wheeler, B. D., Shaw, S. and Tanner, K. (2009). *A wetland framework for impact assessment at statutory sites in England and Wales*. Environment Agency Science Report SC030232.

Whitehead, G. K. (1960). *The deer stalking grounds of Great Britain and Ireland*. Hollis and Carter, London.

Whitfield, P., St-Hilaire, A. and van der Kamp, G. (2009). Improving Hydrological Predictions in Peatlands. *Canadian Water Resources Journal* **34**, 467–478. doi:10.4296/cwrj3404467.

Willis, A., Phillips, J., Yalden, D. and Tallis, J. (1982). Peak District Moorland Erosion Study: Phase 1 Report. *Journal of Ecology* **70**, 385–386. doi:10.2307/2259901.

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A. and Morris, M. (2011). Ditch blocking, water chemistry and organic carbon flux: Evidence that blanket bog restoration reduces erosion and fluvial carbon loss. *Science of the Total Environment* **409**, 2010–2018. doi:10.1016/j.scitotenv.2011.02.036.

Wishart, D. and Warburton, J. (2001). An assessment of blanket mire degradation and Peatland Gully development in the Cheviot Hills , Northumberland. *Geographical Journal* **117**, 185–206. doi:10.1080/00369220118737121.

Wittichenau, O. (2016). Projekte im NSG "Dubringer Moor" - Accessed at http://www.alt.nabu-sachsen.de/lv/jupgrade/index.php?option=com_content&view=article&id=1001&Itemid=811.

Woo, M. and Winter, T. (1993). The role of permafrost and seasonal frost in the hydrology of northern wetlands in North America. *Journal of Hydrology* **141**, 5–31.

Worrall, F. and Burt, T. (2007). Flux of dissolved organic carbon from U.K. rivers. *Global Biogeochemical Cycles* **21**, 1–14. doi:10.1029/2006GB002709.

Worrall, F., Reed, M., Warburton, J. and Burt, T. (2003a). Carbon budget for a British upland peat catchment. *Science of the Total Environment* **312**, 133–146. doi:10.1016/S0048-9697(03)00226-2.

Worrall, F., Burt, T. and Shedden, R. (2003b). Long terms records of riverine carbon flux. Biogeochemistry. **64**, 165–178.

Worrall, F., Harriman, R., Evans, C., Watts, D., Adamson, J., Neal, C. and Tipping, E. (2004a). Trends in dissolved organic carbon in UK. *Biogeochemistry* **70**, 369–402.

Worrall, F., Burt, T. and Adamson, J. (2004b). Can climate change explain increases in DOC flux from upland peat catchments? *Science of the Total Environment* **326**, 95–112.

Worrall, F., Burt, T. and Adamson, J. (2006). The rate of and controls upon DOC loss in a peat catchment. *Journal of Hydrology* **321**, 311–325. doi:10.1016/j.jhydrol.2005.08.019.

Worrall, F., Armstrong, A. and Adamson, J. (2007a). The effects of burning and sheep-grazing on water table depth and soil water quality in a upland peat. *Journal of Hydrology* **339**, 1–14. doi:10.1016/j.jhydrol.2006.12.025.

Worrall, F., Armstrong, A. and Holden, J. (2007b). Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. *Journal of Hydrology* **337**, 315–325. doi:10.1016/j.jhydrol.2007.01.046.

Worrall, F., Chapman, P., Holden, J., Evans, C., Artz, R., Smith, P. and Grayson, R. (2011a). A review of current evidence on carbon fluxes and greenhouse gas emissions from UK peatlands. *JNCC Report No. 442* 91.

Worrall, F., Rowson, J., Evans, M., Pawson, R., Daniels, S. and Bonn, A. (2011b). Carbon fluxes from eroding peatlands – the carbon benefit of revegetation following wildfire. *Earth Surface Processes and Landforms* **36**, 1487–1498. doi:https://doi.org/10.1002/esp.2174.

Wrightham, M. and Kempe, N. (2006). *Hostile Habitats - Scotland's Mountain Environment*. First. Scottish Mountaineering Trust, Scotland.

Wu, J., Roulet, N., Moore, T., Lafleur, P. and Humphreys, E. (2011). Dealing with microtopography of an ombrotrophic bog for simulating ecosystem-level CO2 exchanges. *Ecological Modelling* **222**, 1038–1047. doi:10.1016/j.ecolmodel.2010.07.015.

Yamulki, S., Anderson, R., Peace, A. and Morison, J. (2013). Soil CO2, CH4, and N2O fluxes from an afforested lowland raised peatbog in Scotland: implications for drainage and restoration. *Biogeosciences Discussions* **9**, 7313–7351.

Yeloff, D. and Mauquoy, D. (2006). The influence of vegetation composition on peat humification: implications for palaeoclimatic studies. *Boreas* **35**, 662–673. doi:10.1111/j.1502-3885.2006.tb01172.x.

Young, J. (1975). Ice wastage in glen Feshie, Inverness-shire. *The Scottish Geographical Magazine* **91**, 37–41. doi:10.1080/00369227508736307.

Yu, Z. (2006). Power laws governing hydrology and carbon dynamics in northern peatlands. *Global and Planetary Change* **53**, 169–175. doi:10.1016/j.gloplacha.2006.03.013.

Yu, Z., Beilman, D. and Jones, M. (2009). Sensitivity of northern peatland carbon dynamics to Holocene climate change. In: Baird, A.J., Belyea, L.R., Comas, X., Reeve, A.S. & Slater, L.D. (eds.) Carbon Cycling in Northern Peatlands, Geophysical Monograph 184, American Geophysical Union (AGU), Was.

Zoltai, S. and Johnson, J. (1987). Relationships between nutrients and vegetation in peatlands of the Prairie Provinces. *Wetlands/Peatlands* 535–543.

9. Appendices

9.1 Appendix A: Feshie papers

This list is by no means exhaustive but indicates some of the research happening in and around Glenfeshie in the past and continues to be studied and presented up to the present day. This list was compiled as part of the literature review search. The categories presented include; Flora, Fauna, Soil, River Feshie, Management, Climate and/or Imagery.

Entry Number	Year	Title	Author	Location	Category	Key Words
1	1906	The Kingussie district: A geographical study	Newbigin	Glenfeshie	Geology, Climate	Meterology, hydrology, population
2	1959	The native pinewoods of Scotland	Marshall & Carlisle	Glenfeshie	Flora	Native pinewoods
3	1962	Cladonia Elongata (Jacq.) Hoffm. In the Cairngorms	McVean	Mòine Mhór	Flora	Ecology
4	1973	Early Mortality and Survival of Self-Sown Seedlings in Glenfeshie, Inverness-Shire	Miles	Glenfeshie	Flora	Mortality and survival of seedlings, woodland regeneration
5	1975	Ice wastage in Glen Feshie, Inverness-shire	Young	Glenfeshie	Climate	Glacial, geomorphology
6	1976	The Terraces of Glen Feshie, Inverness-shire	Young	Glenfeshie	River Feshie	Terraces
7	1979	Glenfeshie: an achievement in Conservation	Primm	Glenfeshie	Forestry	Conservation
8	1983	Bar Development and Channel Changes in the Gravelly River Feshie, Scotland, in Modern and Ancient Fluvial Systems	Ferguson & Werritty	River Feshie	River Feshie	Bar development, channel change
9	1986	Performance and population dynamics in relation to management of red deer Cervus elaphus at Glenfeshie, Inverness-shire, Scotland	Mitchell, *et al.*	Glenfeshie	Management	Red deer
10	1986	A quantitative soil-stratigraphic approach to the correlation and dating of post-glacial river terraces in Glen Feshie, western Cairngorms	Robertson-Rintoul	Glenfeshie	Soil	Terraces; soil-stratigraphic units, Holocene
11	1989	Size-Selective Entrainment of Bed-Load in Gravel Bed Streams	Ashworth & Ferguson	River Feshie	River Feshie	Erosion, geomorphology

Entry Number	Year	Title	Author	Location	Category	Key Words
12	1989	Late Holocene debris cone evolution in Glen Feshie, western Cairngorm Mountains, Scotland	Brazier & Ballantyne	River Feshie	River Feshie	Climatic deterioration, debri flows, paraglacial, radiocarbon dating
13	1991	The geomorphology, conservation and management of the River Feshie SSSI	Werritty & Brazier	River Feshie	River Feshie	Management, geomorphology
14	1992	Third international workshop on gravel bed rivers	Ferguson & Ashworth	River Feshie	River Feshie	Hydrology
15	1993	Variations in weathering processes and rates with time in a chronosequence of soils from Glen Feshie, Scotland	Bain *et al.*	Glenfeshie	Soil	Soil profiles, chronology
16	1998	Variation in soil surface area in a chronosequence of soils from Glen Feshie, Scotland and its implications for mineral weathering rate calculations	Hodson *et al.*	Glenfeshie	Soil	Soil profiles, chronology
17	1998	Engineering methods for Scottish gravel bed rivers	Hoey *et al.*	River Feshie	River Feshie, Management	Hydrology, management
18	2000	Replicated proxy-climate signals over the last 2000 yr from two distant UK peat bogs: new evidence for regional palaeoclimate teleconnections	Barber *et al.*	Mòine Mhór	Climate	Plant macrofossil analysis
19	2000	Temporal measurement of the loss of native pinewood in Scotland through the analysis of orthorectified aerial photographs	Cameron *et al.*	Glenfeshie	Imagery	Native pinewoods, aerial photographs
20	2000	Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey	Brasington *et al.*	River Feshie	River Feshie	Channel morphometry, GPS, GIS, digital elevation modelling, braided rivers
21	2000	Channel change and vegetation diversity on a low-angle alluvial fan, River Feshie, Scotland	Gilvear *et al.*	River Feshie	River Feshie	Channel change, biodiversity, GIS, alluvial fan, river conservation
22	2001	A method for estimating changes in the visibility of land cover	Miller	Glenfeshie	Imagery	Spatial analysis, land cover
23	2001	The Potential for high resolution fluvial archives in braided rivers: quantifying historic reach-scale channel and floodplain development in the River Feshie, Scotland	Rumsby *et al.*	River Feshie	River Feshie	Braided rivers

Entry Number	Year	Title	Author	Location	Category	Key Words
25	2003	Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport	Brasington *et al.*	River Feshie	River Feshie	Braided rivers, DEM, photogrammetry, GPS, sediment transport
26	2003	River Spey Catchment Plan	Scottish Environment Protection Agency	River Feshie	River Feshie	Hydrology, management
27	2004	Using tracers to upscale flow path understanding in mesoscale mountainous catchments: two examples from Scotland	Soulsby *et al.*	River Feshie	River Feshie	Tracers, runoff, models
28	2004	Groundwater-surface-water interactions in a braided river: a tracer-based assessment	Rodgers *et al.*	River Feshie	River Feshie	Groundwater–surface-water interactions, tracers; braided rivers, hydrology, hydroecology
29	2004	Geomorphological changes and trends in Scotland: river channels and processes	Werritty & Hoey	River Feshie	River Feshie	Hydrology, gravel-bed river, management
30	2005	Stable isotope tracers as diagnostic tools in upscaling flow path understanding and residence time estimates in a mountainous mesoscale catchment	Rodgers *et al.*	River Feshie	River Feshie	Isotope, tracers, hydrology, mesoscale, residence times, runoff processes
31	2006	Geological Conservation: Chapter 4 Case Studies	English Nature	River Feshie	River Feshie, Management	Conservation, flooding
32	2006	Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: An initial evaluation	Soulsby *et al.*	River Feshie	River Feshie	Mean residence times, soil hydrology, flow paths
33	2006	Groundwater influence in hyporheic zones: a key control on site selection for Atlantic salmon spawning in a braided river system?	Grant *et al.*	River Feshie	River Feshie	Salmon
34	2006	Cairngorms: A landscape fashioned by geology	Gordon *et al.*	Cairngorms	Geology	Geology & landscape

Entry Number	Year	Title	Author	Location	Category	Key Words
36	2008	Modelling conflicting objectives in the management of a mobile ecological resource: Red deer in the Scottish Highlands	Smart *et al.*	Glenfeshie	Management	Red deer
37	2008	Monitoring and modelling particle and reach-scale morphological change in gravel bed rivers	Rumsby *et al.*	Glenfeshie	River Feshie	GPS, DEM
38	2008	After the Ice: Holocene Geomorphic Activity in the Scottish Highlands	Ballantyne	Glenfeshie	Glacial	Geomorphology, holocene, paraglacial, slope failure, alluvial history
39	2008	Uncertainty in morphological sediment budgeting of rivers	Wheaton	River Feshie	River Feshie	Morphology & sediment
40	2009	Analysing laser-scanned digital terrain models of gravel bed surfaces: linking morphology to sediment transport processes and hydraulics	Hodge *et al.*	River Feshie	River Feshie	Digital terrain model, gravel-bed rivers, riffle–pool morphology, sediment surface structure, semivariogram, terrestrial laser scanning
41	2009	In situ characterization of grain-scale fluvial morphology using Terrestrial Laser Scanning	Hodge *et al.*	River Feshie	River Feshie	Terrestrial Laser Scanning, point cloud, gravel-bed river, sediment surface morphology, terrain modelling
42	2009	Experimental analysis of braided channel pattern response to increased discharge	Egozi & Ashmore	River Feshie	River Feshie	Hydrology, braided rivers
43	2010	Archaeological Walk-over Survey and Mitigation for Cable Undergrounding Project	Peteranna & Fraser	Glenfeshie	Archaeology	Monitoring
44	2010	Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets	Wheaton *et al.*	River Feshie	River Feshie	DEM of Difference (DoD), fluvial geomorphology, morphological sediment budgeting
45	2010	The geomorphological heritage of the Cairngorm Mountains	Kirkbride & Gordon	Cairngorms	Management	GIS, geomorphology
46	2010	Field trip to Glen Feshie, June 2010	Butterfly Conservation	Glenfeshie	Fauna	Count, butterflies & moths
47	2011	Geodiversity of the Cairngorms National Park	Barron *et al.*	River Feshie	River Feshie	Geology, geomorphology & landscape

Entry Number	Year	Title	Author	Location	Category	Key Words
48	2012	Monitoring channel change in gravel bed rivers: hyperscale surface modelling by means of terrestrial laser scanning	Vericat *et al.*	River Feshie	River Feshie	Terrestrial laser scanning, gravel-bed river, morphodynamics, topographic change
49	2012	Glen Feshie, Scotland (The Beauty Of Scotland)	McGeachan	Glenfeshie	Photographs	Landscape
50	2012	Tree Planting in Glen Feshie	Mountain Woodland Project	Glenfeshie	Management	Tree planting
51	2012	Landscape: Pattern, Perception & Process	Bell	Glenfeshie	Management	Deer management
52	2013	Downward migration of radiocaesium in organic soils across a transect in Scotland	Shand *et al.*	Glenfeshie	Soil, Climate	Chernobyl, radioactivity
53	2013	Estimating U fluxes in a high-latitude, boreal post-glacial setting using U-series isotopes in soils and rivers	Andersen *et al.*	River Feshie	River Feshie	Weathering, uranium, soil
54	2013	Glen Feshie	Marshall	Glenfeshie	Management, archaeology	History, archaeology
55	2013	How do braided river dynamics affect sediment storage?	Balcerak	River Feshie	River Feshie	Hydrology, geomorphology, fluvial
56	2013	Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river	Wheaton *et al.*	River Feshie	River Feshie	Morphological sediment budgeting, DEM differencing, geomorphic change
57	2014	Terrestrial Laser Scanning of Braided Rivers: River Feshie, Glenfeshie Estate, Scotland.	Kasprak *et al.*	River Feshie	River Feshie	Terrestrial Laser Scanning (TLS), geology, hydrology
58	2014	Scotland's Landscape: Glenfeshie	BBC Scotland	Glenfeshie	Management	Forestry & restoration

59	2015	Development of recent chronologies and evaluation of temporal variations in Pb fluxes and sources in lake sediment and peat cores in a remote, highly radiogenic environment, Cairngorm Mountains, Scottish Highlands	Farmer *et al.*	Loch Einich and Great Moss	Climate	Sediment core
60	2015	Dick Balharry's vision for land use in Scotland	Balharry	Glenfeshie	Management	Deer, estates, land management
61	1980-2007	Glen Feshie	Werritty & McEwan	Glenfeshie	River Feshie	Hydrology, geomorphology, fluvial
62	No date	Deer Management in Glen Feshie: Main Features of the Situation	Cairngorms Campaign	Glenfeshie	Management	Deer

9.2 Appendix B: Field work diary

Summary table of activities undertaken and site specific observations during study site visits.

Note: AB=Andrew Black, TB=Tom Ball, OB=Olivia Bragg, RB=Robert Bryder, KD=Kerry Dinsmore, JW=Jamie Whitelaw, MD=Michael Delpippo, FS=Fiona Scott, JS=James Slater, TM=Thomas MacDonell, AA=Alice Ambler, BM=Ben Murray, SAGT=Scottish Association of Geography Teachers, spectro::lyser =spectro

Date	**Time (LT)**	**Accompanying Personnel**	**Description**	**Weather conditions**	**Feshie Bridge River Level (m)**
08/10/2013	0720 - 1830	AB, TB and KD	Look over and introduction to the study site. Sample taken for GHG analysis at CEH.	Snow covered and misty	0.60
06/11/2013	0600 - 1900	AB	Stuck in snow, emptied SG and looked at AWS.	Snow covered	0.62
08/11/2013	0600 - 1900	AB and MSc student	River too high to safely cross so emptied SG 06, 07, 10 & 11. Girsle pool stage reading taken.	Snow covered and sunshine	> 0.80
19/11/2013	0630 - 2000	AB	Emptied SG 01 & 02; HOBO removed: Ponie's well; HOBO removed and installed at new location: CD U, CD NW, CD L; New HOBO in same location: CD NE; and New HOBO in new location: Eidart	Snow covered & cloudy	0.61
21/02/2014	0700 - 1745	AB	River too high to safely cross so walked on foot to empty SG 06, 07 and 08. Used vehicle to get part way to SG 09 & 10 then walked on foot over snow but couldn't locate due to snow cover. Emptied SG 11 next to road.	Snow covered and cloudy	~ 1.00
13/03/2014	0630 - 2000	AB	Girsle Pool and Chomhraig gauging.	Snow covered and dry	0.74
13/04/2014 - 16/04/2014	0800 - 2000	AB and MSc students	Emptied SG 01, 02, 03, 04 and 05. Started off flood risk survey for gate lodge at Glenfeshie Estate. Flow gauging on Mòine Mhór.	Mix of sunshine, rain and wind. Still snow patches on Mòine Mhór.	0.70 - 0.80
08/05/2014	0630 - 2200	RB	Flow gauging and water sample collected at Eidart U, CD NE, CD NW and CD L. Walked on foot from CD to Eidart due to snow cover.	Rainy showers. Snow packs remaining on Mòine Mhór.	~ 0.80, water coming in buggy

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
15/05/2014	0630 - 2300	RB	Flow gauging and water sample collected at Gar E, Gar NW, MM SE T, CD U, CD L, CD NE and CD NW. Scoped out spectro::lyser site on MM SE T. Depth ~ 65 - 70 cm at 15:15 LT. Flow rate 30 cm up from bed 36 rot/30 sec and 27 rot/30 sec.	Cloud cover, dry and slightly windy. Some snow packs remain but reduced from last week.	0.71
02/06/2014	0640 - 2100	AB, TB and OB	Installation of spectro::lyser at MM SE T. Solar panel and cage deployed. Instrument set logging at 1600 LT. MM SE stage taken. MM SE HOBO downloaded at 1630 LT. Set on delayed start to start logging at 1645 LT.	Foggy and drizzly all day	0.66
10/06/2014	0900 - 1900	AB and MD	ISCO machine (6712/Envitech) set off at 1150 LT at Gar E to take a sample every hour for 24 hours. Named 2Feshie. Went to collect 11/06/14 & autosampler had only collected 16 bottles, programme stopped, low battery, 'errors have occurred during this programme' message. Some water present in bottom of sampler. MM SE autosampler battery ran out of charge one 12 ah was not enough, would have needed two. Collected 11 samples. Cleaned optical lens on spectro.	Dry and some showers (heavy rain at night)	0.64
11/06/2014	0900 - 2000	AB and MD	Clearing cage of peat debris 1125 GMT. Gar E stage – 3 cm 1255GMT (angle iron above water on opposite bank from HOBO).	Dry and warm	0.67
24/06/2014	0930 - 2200	AB,TM and Wes	Went to look at spectro site. Wes and TM are going to build a stand for two solar panels. The cage had been tipped. The unit was still under water. From 11.28 until 12:30 LT the cage was out of water. The cage was cleaned at 12.35 LT and was put back in the water to start logging again at 12:40 LT. To Do: Send a diagram to Thomas and Wes about how the spectro should be positioned in the water. AB finished off DGPS work at gatehouse location (Chomhraig –wooden bridge).	Sunny and clear	0.81
09/07/2014	0600 - 2230	RB	Collected water samples and flow gauged at all sites. Analysed water samples in spectro. RB put in two posts to support solar panel with piece of rope. Downloaded motion cam pictures. Battery check 13.53 v (sunny, panel connected).	Sunny and dry	0.65
22/07/2014	0600 - 2130	None	Collected water samples and downloaded spectro. Met AC on the MM.	Sunny and dry (quite a few black flies)	0.50

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
12/08/2014	0530 - 2330	RB	Walked on foot from Auclean footbridge; had to ford Garbhlach (quite hard) as level too high to ford Feshie. Gauged Gar E, Gar NE and CD L. Spectro had been washed d/s by high flow. Plastic box destroyed. Took unit home to dry out.	Wet, windy and foggy	High (~ 2.18)
23/08/2014	0600 - 1800	AB	Checked battery voltage = 12.76 v. Re-installed spectro in MM SE T. Took water sample 1010 LT. Put probe back into logger mode at 1040 LT. Downloaded HOBO 1122 LT. Probe put back in water at 1131 LT. Flow gauged at MM SE T. SG 11, 01, 02, 03, 05, 04, 09, 10, 06 and 07 emptied. Download HOBO at 1432 LT at Feshie Bridge (SEPA site). S/N 10563906 New HOBO put in undergrowth at Feshie Bridge (SEPA site).	Sleet on MM but overall dry sunny day	0.77 (on the verge of too high for buggy)
04/09/2014	0715 - 1930	AB and Kris	AB had a meeting with TM and emptied some rain gauges. Kris and I went up to the MM to collect water samples and take stage readings. Could not get access to Eidart as shooting was going on. Tested water samples in spectro.	Dry and sunny	0.58
11/09/2014	0600 - 2000	MD	8:45 am on the MM seen 3 herds of red deer. Hinds & stags. One herd near MM SE T, on near CD and one between CD and Eidart. All moving SW. 20+ deer in each group, seen over 100+ deer. MD done transect level and deer dung count at Eidart and CD U. Collected sample at Eidart. Took stage readings at CD U, CD tribs, Gar E, Gar NW and MM SE T. Downloaded spectro and read SG 03 and 11.	Warm, dry and sunny	0.50
24/09/2014	0600 - 2200	MD	MD done vegetation quadrat survey and dung count at Eidart and CD U. Water samples collected at Eidart, CD U and MM SE T. Downloaded spectro data.	Drizzly and windy	0.46
09/10/2014	0600 - 2200	MD	River level too high for buggy so went on foot. Took buggy over Auchlean footbridge and left buggy near forest edge then went on foot up over Meall Dubhag (998 m). Seen ~15+ deer at Garbhlach on foot to MM. Seen 1 stag & two hinds 1430 LT. Downloaded HOBO at CD U, CD tribs and CD L. Overnight stay in Mill Cottage.	Foggy at times and dry	~ 0.80
10/10/2014	0830 - 2030	MD	Buggy able to cross river. Downloaded and re-set the rest of the HOBOs, collected WS's and analysed in the spectro. Seen 3 stags on MM (1130 LT). MD done vegetation survey and dung count.	Dry & mild. Fog and heavy rain started just as we were leaving at 1630 hours.	~ 0.77

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
30/10/2014	0600 - 2000	MD	Flow gauging at Eidart and CD U. Collected water samples at Eidart, CD, CD NE, CD NW and MM SE T. Analysed samples in spectro and downloaded data. Emptied MM SG 134 mm 1510 LT. MD carried out his dung count and vegetation line transects.	Wet and misty	~ 0.74
04/11/2014	0600 - 2130	AB	Advised not to cross Feshie. Andrew completed dGPS work for flood risk assessment for planned gatehouse. Emptied SG 12 together. Emma emptied SG 06,07,08,09 and 10. Seen a man flying his eagle at SG8.	Sleet on higher ground and showers throughout the day	~ 0.77
12/11/2014	0700 - 1630	TB	Tried to cross Feshie in amphibious/military vehicle but was too high and fast for TM. Instead emptied AB's rain gauges on this side of the Feshie then dropped all the equipment back at the lab (autosampler/battery for Toms probe etc.).	Rainy all day	Event of ~ 1.4 m. River level at time only read 0.7 but it was increasing throughout the day.
28/11/2014	0615 - 2000	AB and MD	No one at estate so went on foot to MM. Collected water samples. Laptop had a flat battery so not able to download data.	Fog, drizzly but mostly dry	0.67
05/12/2014	0600 - 2030	AB	Emptied SG 06, 07, 08, 09, 10, 11 and 01. Downloaded spectro, took a while as low battery. Fitted 2nd fatmax box. Lost my phone.	First snow arrived. Track still accessible. Cold and dry.	0.60
07/01/2015	0600 - 2130	RB	Took buggy to just before Garbhlach then left there due to snow covered track. Changed battery on the spectro (before: 10 v, after: 12.59 v). Changed the logging interval to 1 hour. Emptied MM SG and collected water samples as close to HOBO locations as possible (due to snow cover conditions). Observation: There was various snowpacks covering the water and some samples contained high levels of SS. The snow had peat lying on top of it. The snow was acting as a transport mechanism for SS (worth more investigation).	Snow covered and windy, track half visible in parts, managed to get buggy onto the plateau. River level too high on the way back so had to go on foot back and leave buggy on the other side of the river.	0.90 +
13/02/2015	0530 - 1945	RB	Met AB at 0800 at Feshiebridge to look at Sarasota unit. Went up to estate at 0930 and Billy gave us a lift up the hill with the battery. Changed over battery and spectro site. Went on foot back down the MM. Emptied SG 03, 02, 01, 06 and 07.	The white room, no watercourse or track visible on plateau. Misty and cold but dry.	0.60 (low – easy to wade back across)

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
27/02/2015	0645 - 1900	AB	Mikey drove us up the hill in the track vehicle but it lost all drive part way up the hill to the MM. Went back down the hill and got a buggy and went to SG 12 and downloaded the TBR which needs a new battery. Read SG 12 and 11. AB had a meeting with TM and Spey Fishery at 1 pm about declining salmon populations and I went off and read SG 06 and 07. Tried to read SG 09 and 10 but too much snow on the hill. TM mentioned that I could try collating all information on what is known about Feshie, what research has been done.	Dry but Feshie is still snow covered	0.80
11/03/2015	0630 - 1800	AB and TB	TM took us up the hill in the Hagglund. Had to dig through ~ 1.2 m of snow to reach the river. TB installed his probe. I downloaded spectro data and wiped the probe. Took water samples. AB carried out a flow gauging on MM SE T. Went down the hill and met an employee from CEH at the Allt a' Mharcaidh at 1400 LT.	Dry to start then snowy and windy on MM	0.80
27/03/2015	0745 - 1900	TB	Took buggy up the hill then went on foot to MM. TB checked his instrument but forgot the download cable. I downloaded the spectro. We dug out the stream and flow gauged.	Dry, still a lot of snow on the plateau	0.77
14/04/2015	0600 - 2000	AB	River level too high to cross. Emptied SG 11 and 12. Changed battery and downloaded Chomhraig TBR (next to SG 12). Gauged Chomhraig. Timed sticks floating down Feshie at Grilse Pool as Feshie was too high to gauge. Visited AWS 3 (at the top of estate) Emptied SG 06, 07, 08, 09 and 10 with Wes. Visited gliding club weather station. To do: arranged to take Wes around the rest of the SG's next Wednesday. Print of numbers and bring cable ties to label all SGs.	Drizzly and windy	~ 1.00
20/04/2015	0630 - 1630	TB	A lot of snow melt, track almost fully accessible, patches remain at top of Coire Garbhlach and Garbhlach stream. Downloaded TB's instrument (Vaisala M170 Link > Instrument > Download). Motion cam downloaded. TB collected some headspace samples: technique; take in water, squirt out until at 40, create 20 headspace, attach needle and cover, shake underwater for 60 seconds, remove cap and squirt gentle out excess from needle, push headspace into exetainer. 1.3 ^{o}C ambient temp. 6-8 ambient. Removed spectro and cleaned then placed back in higher position in stream.	Dry and calm	0.70

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
22/04/2015	0600 - 1900	Wes	Showed Wes around all 12 SG's and labelled them. Changed battery and downloaded data at Luig_new (next to SG 10).	Sunny and warm	~ 0.74
09/05/2015	0700 - 2000	AB, 2nd years and SAGT	TM gave a presentation on what has been going on in Glenfeshie. I went up to MM with Liz to download spectro::lyser. AB showed visitors the Feshie. Track still snow covered at Coire Garbhlach and Garbhlach stream. Spectro still buried but snow pack falling in around the equipment.	Sunny with some showers	~ 0.60
14/05/2015 - 15/05/2015	0630 - 1900	JS	JS done dGPS work on Chomhraig both days. Stayed overnight at Mill cottage. Downloaded 5 HOBOs: CD U, Gar E, Gar NW and CD NE. Eidart, CD NW and CD L were inaccessible due to snow cover. Analysed water sample in spectro, cleaned out (large part of grass in window). Gas sample collected for TB, unable to download his instrument. Lost upper two parts of flow gauge. Interesting observation 5m u/s of CD U HOBO, peat on grass and bottom of snow pack, pics taken, may create higher SS in water? Also observed at CD L, Gar and MM SE T. Took 4 gas samples for TB, 4 from MM SE T (4) and 2 ambient (labelled 5 & 6). Tried to download TB's probe but unsuccessful.	Sunny (Thu) and dry/windy (Fri).	~ 0.70
20/05/2015	0645 - 2000	BM	Found the two rods that I dropped from last trip up. Tipped out MM SE SG and will start re-measuring next trip up (remember cylinder!). Downloaded atmospheric HOBO and spectro and reset. 1105 LT downloaded TB's probe onto my laptop as software not on AB's laptop. Tried digging at CD NW for HOBO but no luck ~ 2 m of snow depth. Peat bund down at CD L removed; does the pressure of the snow mean that the peat gets taken up in the snow, resulting in the layers of peat seen in the snow?	Dry and windy with some sunshine	~ 0.70
28/05/2015	0630 - 1930	Wes	Emptied SG 01 to 12 with Wes. Went up to spectro site. Snowing and windy on MM. Power had failed on autosampler, only managed to take 3 samples. Battery voltage was 0 v. Wes was too cold to stay and flow gauge. Forgot to empty SG - will do next trip. Downloaded and cleaned spectro.	Snowy, drizzly and windy	~ 0.65
10/06/2015	0700 - 2100	TB	TB reinstalled probe & took gas samples. Water samples and stage readings were taken. Spectro was downloaded and cleaned. Autosampler top switched and set to take a daily sample at 1415 LT.	Sunny	0.60

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
			Took water & gas samples at Gar E and stage reading.		
02/07/2015	0600 - 2230	OB	Southampton team were up this week so I picked OB up at water sports centre where she was staying. Wes gave me back the lost phone and I emptied SG 04 for him. Downloaded and re-set remaining 3 HOBOs at Eidart, CD NW and CD L. OB showed me her probes that the Southampton people had put in. OB also had handheld devices to monitor Temp, Con & pH in the water. Analysed water samples in the spectro. The broom handle had snapped off which had been holding TB's probe, it had been washed downstream. The probe was put on a new broom handle.	Warm, muggy and dry	0.50
06/07/2015	0630 - 2200	JS and FS	JS finished off dGPS work in the Chomhraig. FS was shown around the MM as she wants to continue MD's dissertation. FS can't start fieldwork until late Aug/early Sept as in Yorkshire. Flow gauged Eidart, Gar, CD U and MM SE T. Analysed autosamples in the spectro. Autosampler had started re-filling bottes (*check that this is just the way it was set-up*).	Dry and warm	0.60
15/07/2015	0545 - 2330	RB	Observation: black material absorbed into decaying plant material at snowpack edges and near riverine bankside vegetation in distinct lines, does not absorb into new growth. Samples and flow gauging at all sites. Analysed samples in spectro. Collected head space samples, set TB's probe and autosampler to GMT. Battery voltages: probe 11.8 v, spectro & panels: 13.98 v, autosampler: 11.13 v replaced with 11.9 v. Set autosampler for daily samples at 0600 GMT. Set up motion cam at Eidart, mapped out a suitable area at Eidart for erosion studies. CD L HOBO mounting has moved (bank slip).	Mostly dry and warm	0.60
30/07/2015	0600 - 2330	OB and RB	OB emptied her dipwell and then took me around the site while we looked at vegetation and collected water samples and stage readings. RB took down the Sarastoa at Feshiebridge then cycled up to the MM and met us at the spectro site. RB hooked up Toms probe to one solar panel and the autosampler to the battery. RB also fixed the connections on the spectro battery. Samples collected from the autosampler were analysed in the spectro. The level switch was set up for the autosampler. Battery voltages checked; spectro: 12.71 v, probe: 12.53 v.	Mostly dry and cool (sunny in the evening)	0.60

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
14/08/2015	0600 - 2200	AB	Went up to AWS Druim nam Bo so AB could check on it - reverted back to original programming and seems to be working OK again. Then split up. Gar autosampler filled 6 bottles and then overfilled bottle 7 and stopped. A lot of water was sitting in the bottom of the sampler. Battery changed and programme re-set to take daily samples at 7 am on Sat 15 Aug. MM SE T autosampler triggered by stage trigger on Mon 3 Aug at 13:53 and took 24 samples at intervals of 30 minutes. Analysed was sample collected in the autosampler but didn't capture an event. Tried to re-set autosampler to trigger at high flow but not sure if done correctly. Downloaded Tom's data but didn't have time to collect gas samples. Lots of midges!	Dry and still	~ 0.55
27/08/2015	0600 - 2030		Grouse seen after river crossing. Brown grouse seen on plateau from buggy near spectro site 0855 LT. Lost foot to flow gauge at Eidart. Motion cam downloaded, not sure if put memory card back in correctly. Measured some peat blocks seen on CD and Gar E. Gar E autosampler still not working, took 7 samples then overflowed, bottle one also full. Took water samples at all sites and stage readings.	Misty and heavy showers	0.60 very flashy – lucky to get across and back
01/09/2015	0545 - 1930	RB	Downloaded at re-set HOBO (0730 GMT) at Feshiebridge. Foot off flow gauge found! Took stage readings at all sites. Downloaded and re-set CD NE HOBO - half out of the water but right way up (re-set 1000 GMT). Deployed buckets at Eidart, CD and MM SE T catchments. Checked stage switch on autosampler at SE trib and it worked fine therefore it must be the sampler that is not recognising the switch. Voltages on batteries are fine: Spectro 12.93 v and probe 12.97 v. Set sampler up to trigger when it touched level. The river rose in about 20 minutes and reached the level switch. Took stage reading not long after I arrived and then again during the event. Tried to flow gauge but manual counter box was not working.	Rain all day and in the mist	0.54 (but rose that evening – big event peaked at 0.97
03/09/2015	0600 - 1600	FS	Seen cowberries at Eidart, FS took pics. Conditions very poor, heavy rain, mist, high winds. Had to get off hill as FS was cold and soaked. Conditions not suitable for looking at vegetation. Abandoned plans for overnight as weather was forecast similar for the next day and I was not sure about safe river crossing. Took 1 water sample and stage reading	Heavy rain, wind and fog	0.77 (Davie went ahead in land rover to create bow wave and on verge of safe

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
			at Eidart, CD tribs, CD U and Gar E. Rivers were very full but did not have any flow gauging equipment with me (or time to estimate).		crossing back)
09/09/2015	0600 - 2230	FS	Changed Gar E sampler for one that works and set it on level switch. Flow gauged at Eidart, CD L, CD NE & CD NW with OTT MF Pro. Analysed water samples and autosamples collected in MM SE T.	Sunny	0.50
11/09/2015	0600 - 2230	AB	AB had a meeting with TM in the morning – AB took away a box with folders of information from 1970's about deer numbers in Feshie. Drove to upper Feshie with AB in the buggy to where the Eidart meets the Feshie. AB took some pictures as he hopes to install a gauging station here. Then went up to the plateau. Gauged MM SE T, Gar NW and Gar E while AB went to AWS. Then went to the AWS at gliding club.	Windy	0.55
30/09/2015	0600 - 2200	FS	FS started fieldwork using Michelles old transects. I carried out peat block survey. Downloaded spectro::lyser and TB's probe.	Sunny and calm	0.50 (low)
14/10/2015	0730 - 2130	OB and AB	Supervisory meeting with AC, AB, OB, & TM from 1000 - 1200 at SNH office Aviemore. Went up the hill in the afternoon with OB in a buggy. Downloaded spectro & TB's probe & took some gas samples at MM SE T. Took water samples and stage readings at MM SE T, CD U, CD NE, CD NW and Gar streams. Checked on autosamplers – MM SE T set on level switch it had collected sample Mon 21 Sept but no change in colour so threw away and re-set. Gar E autosampler still not triggered yet but battery appears to still be working.	Dry and cool	0.50
28/10/2015	0600 - 2000	FS	FS set up dGPS and took points of where she done her vegetation samples and also took peat depth measurements, I flow gauged CD U, CD L and CD NE, Eidart and MM SE T. Spectro also downloaded.	Misty, drizzly and some wind	0.55
14/11/2015	0550 - 1830	JW	Got buggy across river with help from Davie creating a bow wave. Managed to drive part way up track (just before Coire Garbhlach and left buggy due to amount of snow). Went on foot to plateau. Rivers were all slush, could not find HOBOs. Managed to download spectro, set to hourly recording. Checked battery voltages - 12.51 v.	Snow showers and some wind	0.85
17/11/2015	0545 - 2000	OB	Re-erected Southampton tripod. Dug down 2 ft of snow to remove Gar E hobo and OB dug out the autosampler. Downloaded Gar NW HOBO. Went to spectro site, huge ice blocks so could not get access to HOBO. Went to CD L and downloaded HOBO but could not re-launch so took it	Fog in the morning, cleared and then snow again late afternoon	0.85

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
			back home. Managed to get buggy to Gar E layby but not beyond due to snow.		
03/12/2015	0545 - 2000	OB	Parked down by SG 01. Wend to MM SE T, downloaded HOBO and atmospheric HOBO, spectro data and TB's DIC data. Battery level at 12.41v.	Snow covered but dry	0.90 then down by the evening
24/12/2015	0530 - 1530	RB	Went up to estate but no one was there. River was too high to cross so went down to Feshiebridge and looked at Sarasota.	Sleety shower, poor conditions	~ 1.20 – too high to cross
08/01/2016	0530 - 2030	RB	Ford has changed. Wes & Davie say it changed after new year. Now more difficult to cross. Parked buggy on flat before Coire Garbhlach. Went on foot to plateau. Downloaded spectro and TB's probe. Checked battery – 11.93 v and cleared solar panel. Looked for HOBOs at CD L and U but no success.	Snow covered but calm, sunny and cold day	0.80
01/03/2016	0515 - 2030	RB	Ford and been re-done so now easier to cross again. Parked at Ponies well area and went on foot to plateau due to snow cover. Checked battery voltage - 12.18 v. Had trouble downloading spectro so had to disconnect power and then managed to download successfully. No files recorded on TB's probe – maybe an error on my part – check if it works next time if not problem with instrument. Walked to CD L – couldn't access HOBO as snow covered so put in a new installation upstream of original location in an area where stream was uncovered. Dug for CD U with no luck – left spade up there so can collect next time.	In the mist most of the day, windy and occasional snow showers. Brightened up briefly as we descended at 4.30 pm.	0.60 morning then ~ 0.85 later on – a lot of melt and some rain would have put the level up
30/03/2016	0530 - 2100	RB	Ford is difficult to cross again. Tree has come down and river is flowing down one fast section. Battery voltage 13.85 v. Equipment list for write-up: Batteries 2x12v 110 Ah NUMAX CXVX31MF wired in parallel. Solar panel/chargers: 2x PV Logic STPO43 43 W, 17.5 v, 2.64 A wired in parallel. TB's DIC probe not logged, problem with probe as 0 % memory used. Spectro downloaded and reset 0931 GMT. Visited CD L temporary HOBO location and took a stage reading. Metal detector was used to find CD U HOBO (under ~ 1.2 m of snow). The vertical bar has been bent into the bank under the weight of the vegetation. Took stage reading. Looked for CD NW (near) trib – no luck. CD NE (far) downloaded and re-set – it was 95 % full. Walked to Eidart. Used metal detector to find motion cam and took it away with us but couldn't locate	Snow covered. Mist in the morning, sunshine in the afternoon, then hailstones at 4 pm and snow.	0.76

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
			HOBO.		
13/04/2016	0545 - 2200	AB and AA	Ford still difficult to cross (tree still down). Took buggy to Coire Garbhlach and went on foot with AA to MM SE T. Spectro downloaded at 0943 GMT, spectro sitting on river bed, log may have snapped. Will need to visit again and dig out TB's probe and spectro. Shovel snapped, tried to dig for probe with no luck. Con 6 ppm, water temp 1^{0}C pH 8.54 at 1100 LT. Went to TBR by SG 10 and put in a new logger. Black bit of funnel was sitting in the tipping bucket – may have impacted on results. Grilse Pool HOBO downloaded and reset, stage + 132 cm 1515 GMT. Chomhraig HOBO downloaded and reset, stage + 146 mm. Feshie hut Baro downloaded and reset, last downloaded in Jan. Went to Gliding club, no data to collect and programming problem.	Misty, drizzly but a mild day	0.68
06/05/2016	0530 - 2030	RB	Seen a lot of young hares, details in deer/animal log. Conductivity probe not working. Both logs snapped at MM SE T. High flow but no current meter so estimated using orange. Spectro downloaded and cleaned and placed on remaining bowed logged. TB's probe has been washed away, walked down stream to try find with no luck. Need to search again on next site visit. Autosampler trigger also washed downstream but found under a snow pack. Taken home to repair. Autosampler set back to 15 min recording. Looked in to previous setting and was actually set at 15 mins 15 seconds. Motion cam redeployed at MM SE T. Battery voltage 15.55 v. Autosampler set to go off at 1200 GMT every 6 hours to try capture the melt period as there was visible turbidity and peat in the water. Still quite a lot of snow up there. Took stage readings at water samples at MM SE T, CD NE and CD U. Looked for CD NW HOBO under snow to download but no luck with metal detector. Haze visible on vegetation above Gar trib on way back to buggy. Buggy had problems on way down the hill, had to reverse off the mountain. Left note for Angus to look at.	Cloudy but warm and dry	0.80
19/05/2016	0600 - 1930	OB	OB changed batteries on all Southampton pieces of equipment. HOBO downloaded which has been sitting in the peat and motion cam pictures at OB monitoring site. Then went to spectro site and downloaded data	Drizzly and windy	0.60

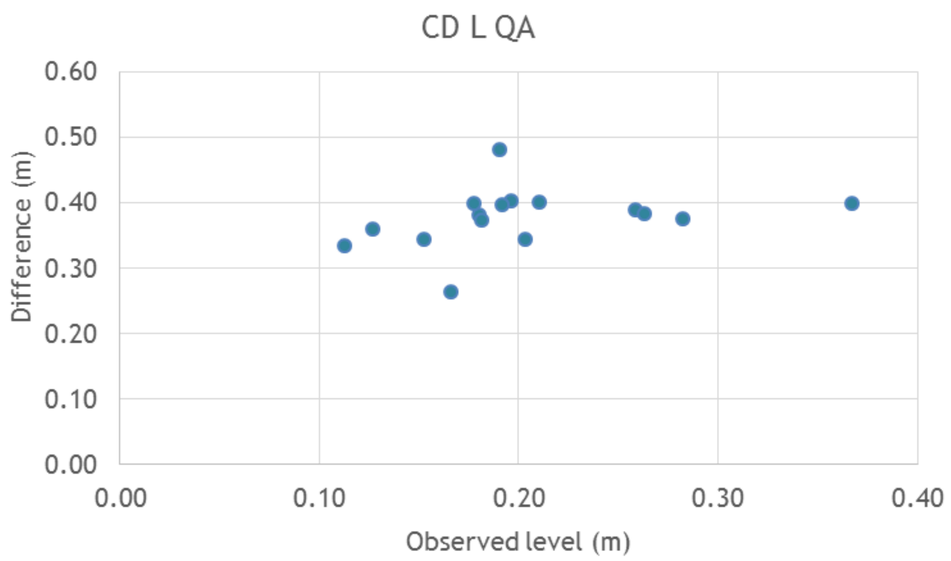
Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
			and cleaned it up. The log placed behind the spectro had been washed downstream. Evidence of sand/silt and peat on far bank of spectro, water must have been flowing over there at some point during snow melt. Autosampler had not taken any samples, have reset again to go off at 15:00 hours every 6 hours then didn't switch it off to see if that will work. Walked down to where MM SE T meets CD to try finding TB's probe, no luck.		
03/06/2016	0545 - 1900	OB	Snowpack still blocking the road at the Garbhlach but other than that track is clear. Water samples taken and HOBOs downloaded at Gar E, Gar NE and CD NW. Flow gauged at CD U and MM SE T. Gar E HOBO only tied on with one cable tie at top – see if this affects results. 88 % full. Felt like first day of summer, black slugs, baby toads, dung beetles and midges. OBS: Dry flecks of peat can lift off the surface – thin and grey and can be transported by wind. Doesn't seem to have happened yet. Evidence of one fleck on grass – pics on GPS. Seen when walking from Gar NW to CD catchment – dry day – dry vegetation all over. CD U HOBO had a big section of bank in-front of it covering it, managed to shift but still sitting in the water. Lots of slime on the rocks in all of the river beds. This made the spectro quite slimy. For next time bring up bottles to collect what is in the autosampler and set up level switch again.	Sunshine in the morning and then misty and dry	0.60 (low)
21/06/2016	0530 - 2130	RB	Took water samples and stage readings at all sites. Flow gauged at Eidart, CD L and tribs and Gar sites. Stage fixed for CD U and new site installed for CD L due to bank collapse (HOBO SN/013). Remove once I have comparable data from the two – few weeks yet. Downloaded motion cam. Set off autosampler with the level switch. Email AB and ask if someone can do rain gauges at end of July for Wes as he is away (done - AB going to do).	Mild but showers throughout the day	0.60
07/07/2016	0530 - 2200	RB	Took 3 headspace samples and 2 ambients at Gar E, Gar NW, Eidart, CD L and MM SE T. Took stage readings and water samples. Analysed water samples in spectro. Tube got stuck in spectro, managed to free eventually. Took some panorama pictures of the catchments but unsuccessful. Set spectro to 30 mins to reduce frequency of visits. Autosampler had not been triggered. Removed second HOBO at	Dry and windy	0.65

Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
			Caochan Dubh - return to AB. No deer seen but evidence of deer - deer scat visible. Battery voltage at spectro site - 14.4 v.		
04/08/2016	0530 - 1900	RB	Rivers very full. Couldn’t flow gauge as had lost the propeller but found again once home. Managed to collect water samples and stage readings at all sites. Visited autosampler, had been triggered on the 10 July. Bottle 1 was taken at 1556 on 10 July. Bottle 23 at 2139 and bottle 24 at 2154. Took samples 1, 2, 6, 13, 20 & 23 back to lab for analysis. No new photos on wildlife camera. Sample set to go off at 13:50 to sample every 30 minutes as while we were up there the river level was very high. Buckets also checked. Gar E astro mat had sediment and peat on it – think it is water borne. Visible trashline 3 m from river. Looks like river had come up and covered it. Took pics on GPS. Estimate of 10 % coverage – some peat, some sand. Mesh had been ripped off Eidart bucket but nothing in it. Astro turf mat at Eidart had ~2 % coverage, most peat around the edges, maybe the water lapped up and deposited it there. Some peat particles in the middle.	Wet and cloudy	0.75
02/09/2016	0615 - 2130	AB	Film crew at Estate, lots of midges! AB showed Wes SG 13a and 13b on lower Feshie. Comparison gauges set up. Dropped AB off at ridge AWS. Went and cleaned spectro, lots of slime/seaweed on it. Battery Voltage 14.33 v. Emptied autosampler bottles and analysed on the spectro. Reset autosampler on level switch. Collected 3 water samples. Went back to AB and emptied SG 04 and 05. Went to gliding club.	Drizzly and mild	0.60
30/09/2016	0530 - 2230	RB	Emptied and reset all 8 HOBOs and high baro at MM SE site. Collected water samples. Carried out peat block survey at all sites apart from MM SE T (as too late). Took away all buckets and astro turf mats and binned. Analysed autosampler samples in spectro and then re-set on level switch. Triggered on 8 Sept at 1250. Noticed blueberries on MM for first year ever. No cylinder but emptied MM SG – 3 bottles full. Lots of seaweed on spectro so data might be spurious. Animal cam downloaded – some nice pics of fawns. Next time – complete block survey at MM SE T.	Dry – hail shower later on in the day	~ 0.70
31/10/2016	0530 - 2000	AB and Wes	Removed spectro::lyser, motion camera, MM SE SG & autosampler. Wes cut off battery stand legs with the chain saw. When we arrived on the MM the rivers were quite full. Andrew carried out a high level gauging on	Rain and foggy on the plateau	Peaked at 0.90, rising all day

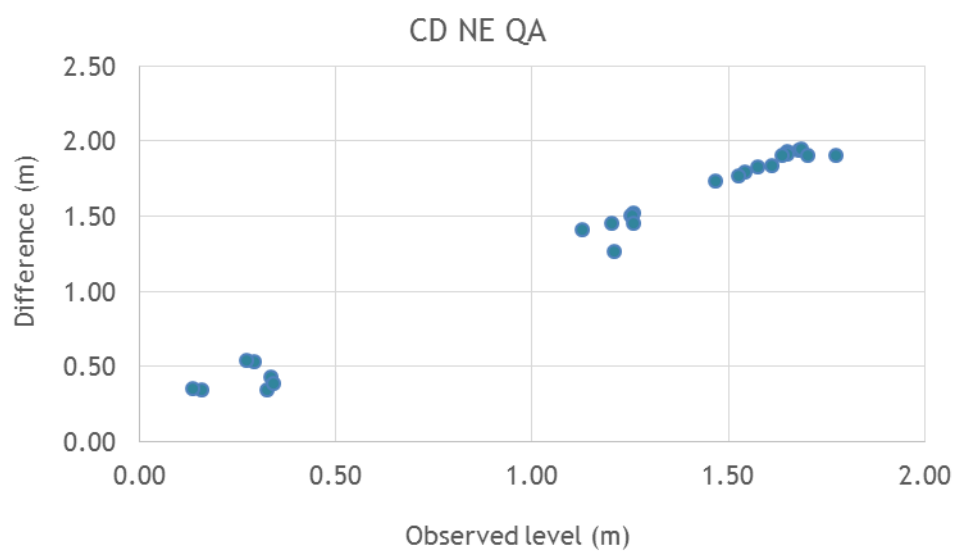
Date	Time (LT)	Accompanying Personnel	Description	Weather conditions	Feshie Bridge River Level (m)
			MM SE T. The autosampler had triggered and was due to take bottle 3 in 11 mins time when we arrived. I stopped it and took a manual water sample in bottle 3 at 1130LT. Bottle 1 10:30am and Bottle 2 10:45 am. AB will redeploy high atmospheric baro at the high altitude weather station inside the box. It was taken down the hill, unable to re-deploy due to rising river levels. AB was taking the spectro::lyser for re-deployment with Thomas to the Northern Estate. AB will return autosampler to the lab.		

9.3 Appendix C: Water level quality assurance

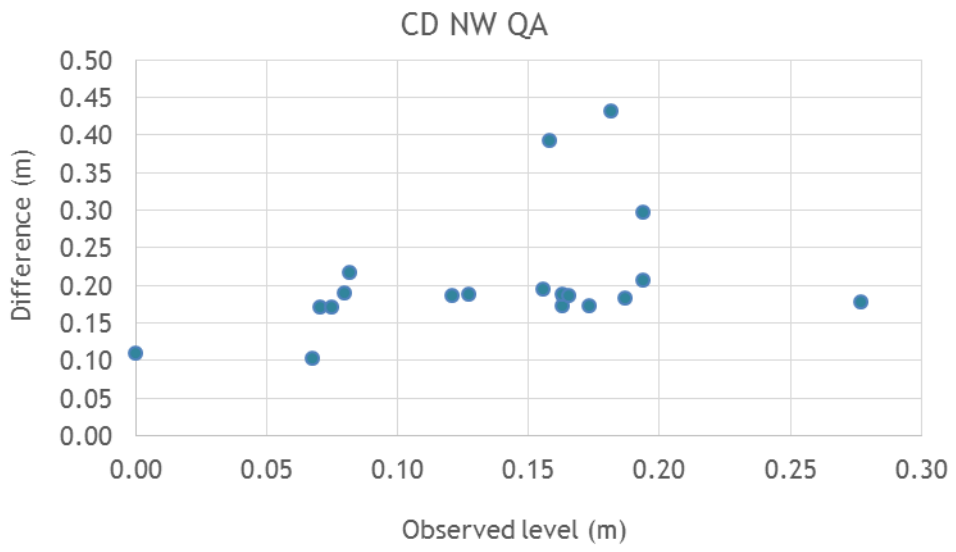
The results for observed water level were quality assurance checked against the logged level from the HOBO. Graphs and comment below shown for; CD L, CD NE, CD NW, CD U, Eidart U, Gar E, Gar NE and MM SE T.



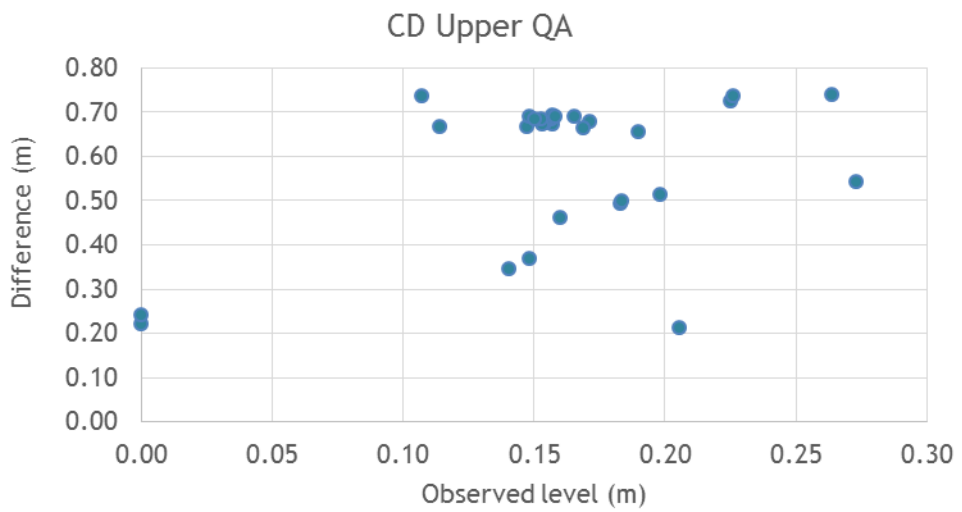
Graph gives an assurance that the difference between the logged and observed level remained similar across the study period. This highlights that stage (angle iron) and HOBO remained in the same place between downloads and across the seasons.



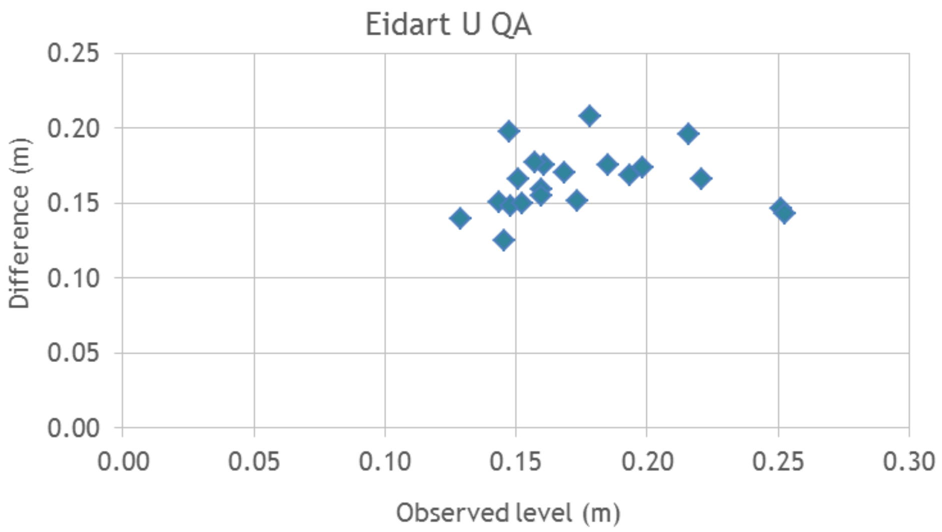
CD NE excluded due to jumps in the logged level from the HOBO. These jumps of over 1 m would not be expected in such a small tributary and were deemed unrealistic.



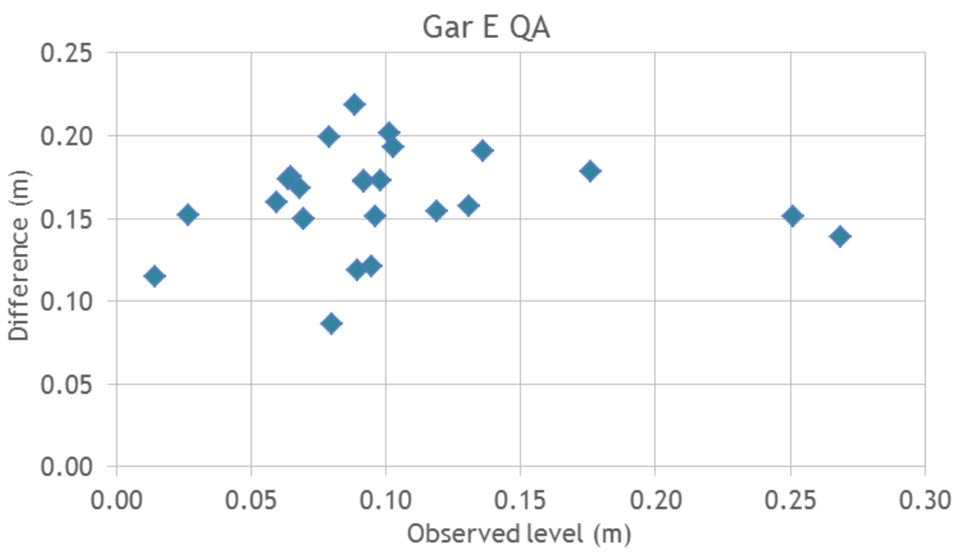
Two dates in August 2014 showed a rise in measured level but it is believed that this is due the stage crumpling under the pressure of snow melt.



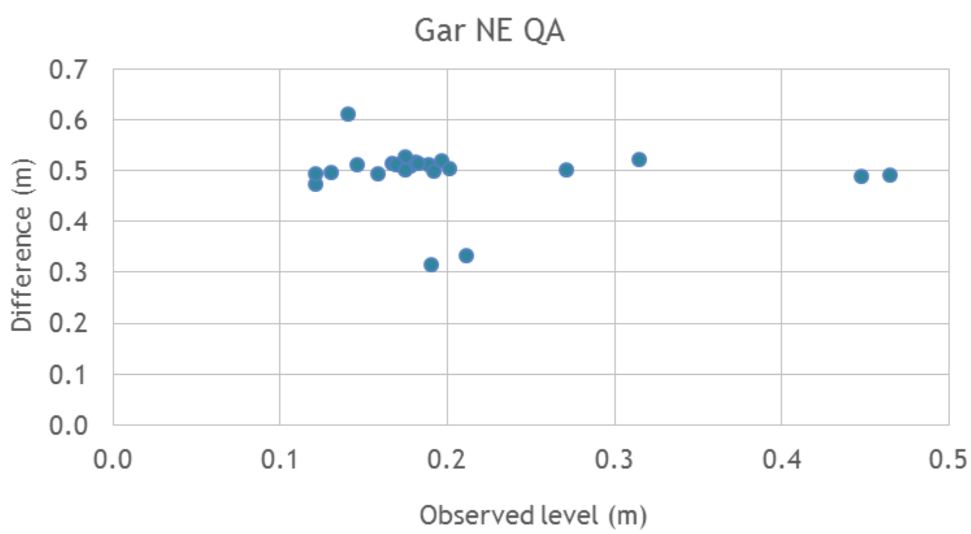
The results for CD U appear more scattered although the main banding is focused around 0.7 m difference.



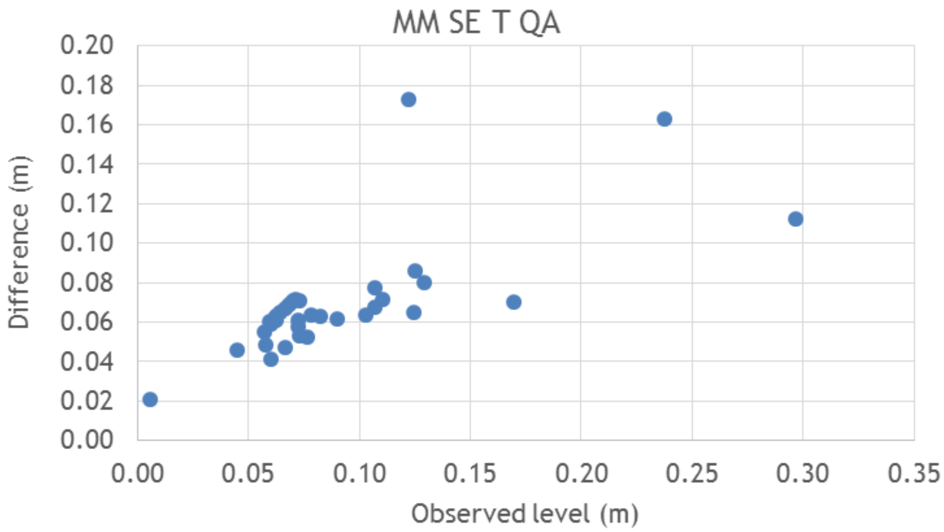
The results are clustered around 0.15 – 0.20 m difference.



The results for Gar E are slightly more variable.



Generally the points are spread across the same level indicating that there was a small difference between the measured and logged level.



An upward trend is apparent at the MM SE T.

The results of these were used in the QA process to help derive the final level series for the monitored streams and corrections were applied to the data where necessary.

9.4 Appendix D: Risk assessment for field work

Author: Andrew Black; Adapted and reviewed: Emma Bryder

Risk	Action taken	Residual risk	Additional measures - and justification if not applied
Road traffic accident	Drive legally, according to road conditions and vehicle capabilities. Check vehicle tyre pressures and tread before departure.	Low	N/A
Falling asleep at wheel	Take a break or swap drivers as required.	Low	Ensure that front seat passengers are aware of the scope for them to help in this regard.
Accident involving use of estate off-road vehicles	Use subject to driver approval by Estate (staff with driving licences only). Drive according to conditions.	Low	N/A
Accident while crossing River Feshie – getting washed away	Cross only at Carnachuin ford (wide river section = safest location). Do not wade across the river if it (a) looks unsafe *or* (b) is known or expected to exceed 0.80 m at SEPA's Feshie Bridge gauge. Use nearest bridge instead.	Low	N/A
Exposure, hypothermia	Take appropriate clothing: wind and waterproof jacket essential (waterproof trousers desirable), hat, gloves, neckwear, extra layers for warmth. Carry survival bag/tent.	Low	N/A
Falling/ankle injury	Wear sturdy boots, possibly also walking poles if desired. Avoid rough or excessively steep terrain where possible, e.g. by keeping to tracks. Do not run – be aware of your vulnerability in the event of a broken ankle. Carry walkie-talkie and/or mobile phone.	Low	N/A

Risk	Action taken	Residual risk	Additional measures - and justification if not applied
Getting lost	Take map, whistle, survival bag/tent, compass/GPS with spare batteries, head torch. Work in pairs if possible. Only follow agreed routes so that, in event of injury/incident, search party will be able to find you. Take mobile phone and/or 2-way radio (phone coverage limited to highest altitudes on red and yellow routes only however). Inexperienced personnel should not follow mountain (yellow) route unaccompanied if risk of needing to navigate in cloud or blizzard. Leave details of routes, personnel, timings and phone numbers with other group members and/or on dash of vehicle at Carnachuin car park.	Low	N/A
Fatigue	Take and eat plenty of food and drink. Turn back if concerned about exhaustion.	Low	N/A
Illness due to drinking from streams	Do not drink from streams (it is difficult to avoid the possibility of a dead animal in the water upstream).	Low	N/A
Falling from mountain bike	Wear cycle helmet. Dismount on steepest downhill slopes if brakes inadequate.	Low	N/A
Illness due to tick bite	Check person for ticks on return from field. Ensure complete removal of any ticks found using tick remover. Seek medical advice if unsure, or see http://www.lymediseaseaction.org.uk	Low	N/A
Sun-burn (risk applies most of year, including effects of reflection off snow)	Appropriate sun-block applied as per instructions.	Low	N/A

Risk	Action taken	Residual risk	Additional measures - and justification if not applied
Capercaillie attack	Stay well away from any capercaillie; particularly in spring and summer.	Low	N/A
Snake-bite	Avoid snakes; do not stand on; only run if you must! Look out for snakes on hot summer days.	Low	N/A
Unstable terrain around river banks, slippery river bed	Take extra care when moving in river. Wear appropriate footwear and life jacket.	Low	N/A
Flood waters	Check forecast for potential flood warnings at time of departure *(If there are flood warnings or alerts in place for the study area, river crossings will be ceased until warnings have passed).*	Low	N/A
Alcohol	All personnel must be in a fit state to carry out work.	Low	N/A
Dehydration	Carry sufficient water.	Low	N/A
Access to land danger from animals	Any fields must be checked before entry and will not be accessed during lambing or containing bulls. Will retreat if any aggression encountered.	Low	N/A
Water-borne disease	Wash hands after going into the water and be aware of the risks of Weil's disease, seek medical attention as soon as returning. Will adhere to strict hand washing and other hygienic procedures: keep eyes, mouth, and nose away from any source of infection. Any cuts and grazes will be covered with waterproof dressings.	Low	N/A
Health hazard: Giant Hogweed	Avoid bank sides where this plant occurs, cover the affected area and wash it with soap and water. In case of feeling unwell, consult a doctor.	Low	N/A

Risk	Action taken	Residual risk	Additional measures - and justification if not applied
Drowning	Extra care will be taken when taking water measurements. Life jackets must be worn.	Low	N/A
Firearms injury/fatality	Always advise estate of plans to visit. Ascertain if any risks from any shooting activity. Keep fully out of shooting areas: be aware that high-powered rifles can reach distances of 20 kilometres.	Low	N/A
Injury from peat corer	Stow safely in vehicle: sharp end pointing away from people. Take care when carrying.	Low	N/A
Deer droppings survey	Avoid contact; maintain hygienic procedures. Wash hands if contact made.	Low	N/A
Lightning strike	Avoid carrying metal rods when lightning is expected. Leave on ground and recover later if necessary.	Low	N/A

9.5 Appendix E: Multiple comparisons test

Tukey's multiple comparisons test of mean differences between the monitored streams

The multiple comparisons test was conducted on Abs_{400} and pH as the results of the 1-way ANOVA (Table 5-14) indicated significant differences. The summary indicates results that have been highlighted as not significant (ns), of significance (*) and of high significance (**).

Parameter	Adj. p value	Stream comparison	Summary
Abs_{400}	>0.999	CD L vs. CD NE	ns
	>0.999	CD L vs. CD NW	ns
	>0.999	CD L vs. CD U	ns
	>0.999	CD L vs. Eidart U	ns
	0.838	CD L vs. Gar E	ns
	0.309	CD L vs. Gar NE	ns
	0.628	CD L vs. MM SE T	ns
	>0.999	CD NE vs. CD NW	ns
	0.992	CD NE vs. CD U	ns
	0.996	CD NE vs. Eidart U	ns
	0.540	CD NE vs. Gar E	ns
	0.103	CD NE vs. Gar NE	ns
	0.265	CD NE vs. MM SE T	ns
	0.997	CD NW vs. CD U	ns
	0.999	CD NW vs. Eidart U	ns
	0.655	CD NW vs. Gar E	ns
	0.162	CD NW vs. Gar NE	ns
	0.387	CD NW vs. MM SE T	ns
	>0.999	CD U vs. Eidart U	ns
	0.951	CD U vs. Gar E	ns
	0.451	CD U vs. Gar NE	ns
	0.809	CD U vs. MM SE T	ns
	0.971	Eidart U vs. Gar E	ns
	0.575	Eidart U vs. Gar NE	ns
	0.889	Eidart U vs. MM SE T	ns
	0.978	Gar E vs. Gar NE	ns
	>0.999	Gar E vs. MM SE T	ns
pH	1.000	CD L vs. CD NE	ns
	0.957	CD L vs. CD NW	ns
	0.911	CD L vs. CD U	ns
	0.295	CD L vs. Eidart U	ns
	>0.999	CD L vs. Gar E	ns
	0.934	CD L vs. Gar NE	ns
	>0.999	CD L vs. MM SE T	ns
	0.999	CD NE vs. CD NW	ns
	0.994	CD NE vs. CD U	ns
	0.068	CD NE vs. Eidart U	ns
	0.996	CD NE vs. Gar E	ns
	0.996	CD NE vs. Gar NE	ns

0.994	CD NE vs. MM SE T	ns
>0.999	CD NW vs. CD U	ns
0.016	CD NW vs. Eidart U	*
0.883	CD NW vs. Gar E	ns
>0.999	CD NW vs. Gar NE	ns
0.837	CD NW vs. MM SE T	ns
0.006	CD U vs. Eidart U	**
0.784	CD U vs. Gar E	ns
>0.999	CD U vs. Gar NE	ns
0.697	CD U vs. MM SE T	ns
0.278	Eidart U vs. Gar E	ns
0.011	Eidart U vs. Gar NE	*
0.165	Eidart U vs. MM SE T	ns
0.836	Gar E vs. Gar NE	ns
>0.999	Gar E vs. MM SE T	ns

9.6 Appendix F: Water chemistry and daily flow

The Excel equation used to calculate gauged daily flow in $m^3 s^{-1}$ in a calendar day was as follows:

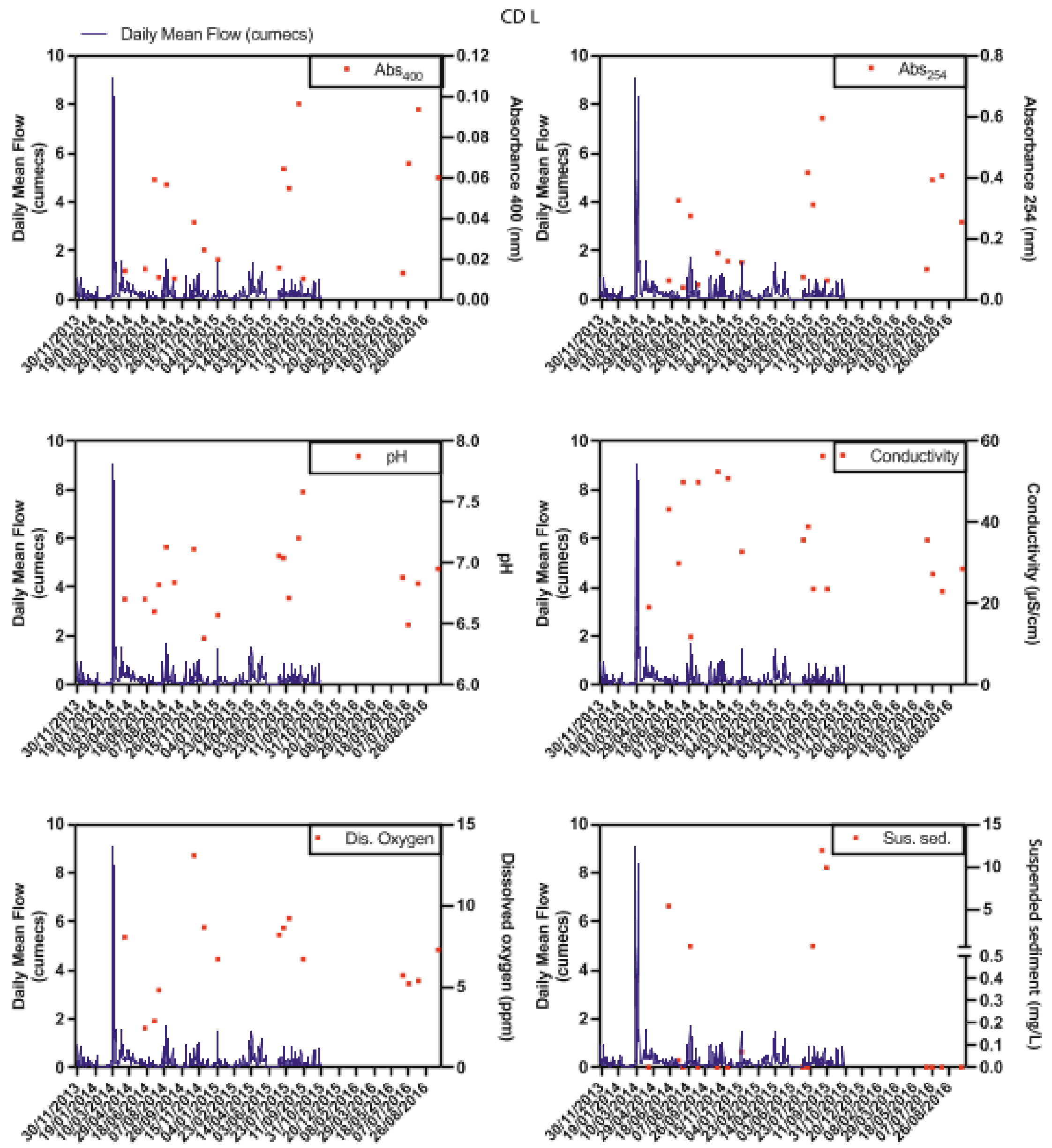
=IF(INT Logged Date/Time)<(INT Logged Date/Time cell below),AVERAGE(Flow A1: Flow A95),"")

Where; Logged Date/Time is that recorded on the HOBO. Flow A1 is from 00:00 of the day you are calculating gauged daily flow for and Flow A95 is 23:45 at the end of that day.

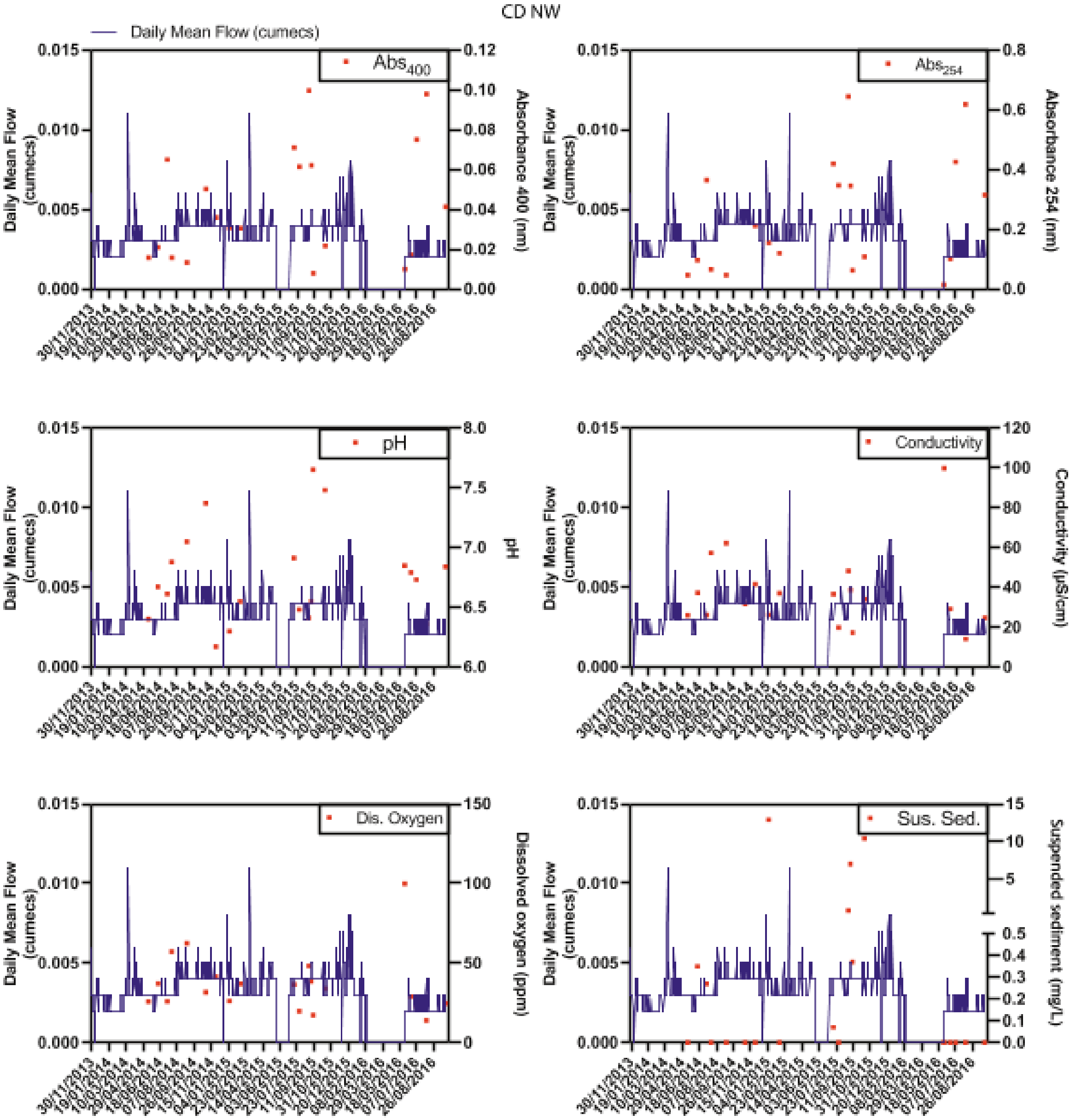
The equation above states that if the integer logged date/time is 15-minutes between one cell and the cell immediately below, then give the mean river flow for one calendar day, if not, then leave cell blank.

Water chemistry results from laboratory analysis and daily flow for each for the monitored streams:

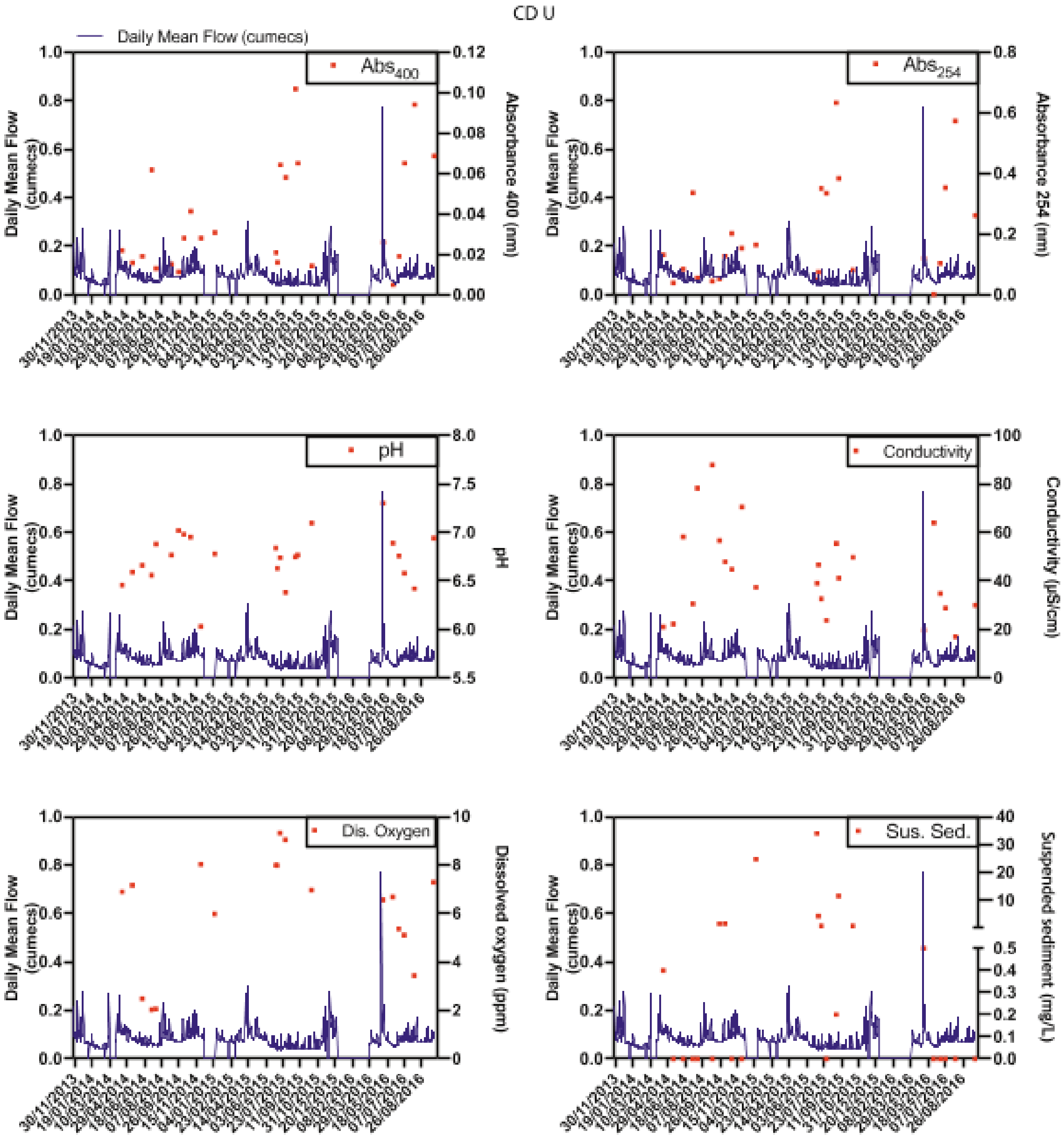
A)



B)

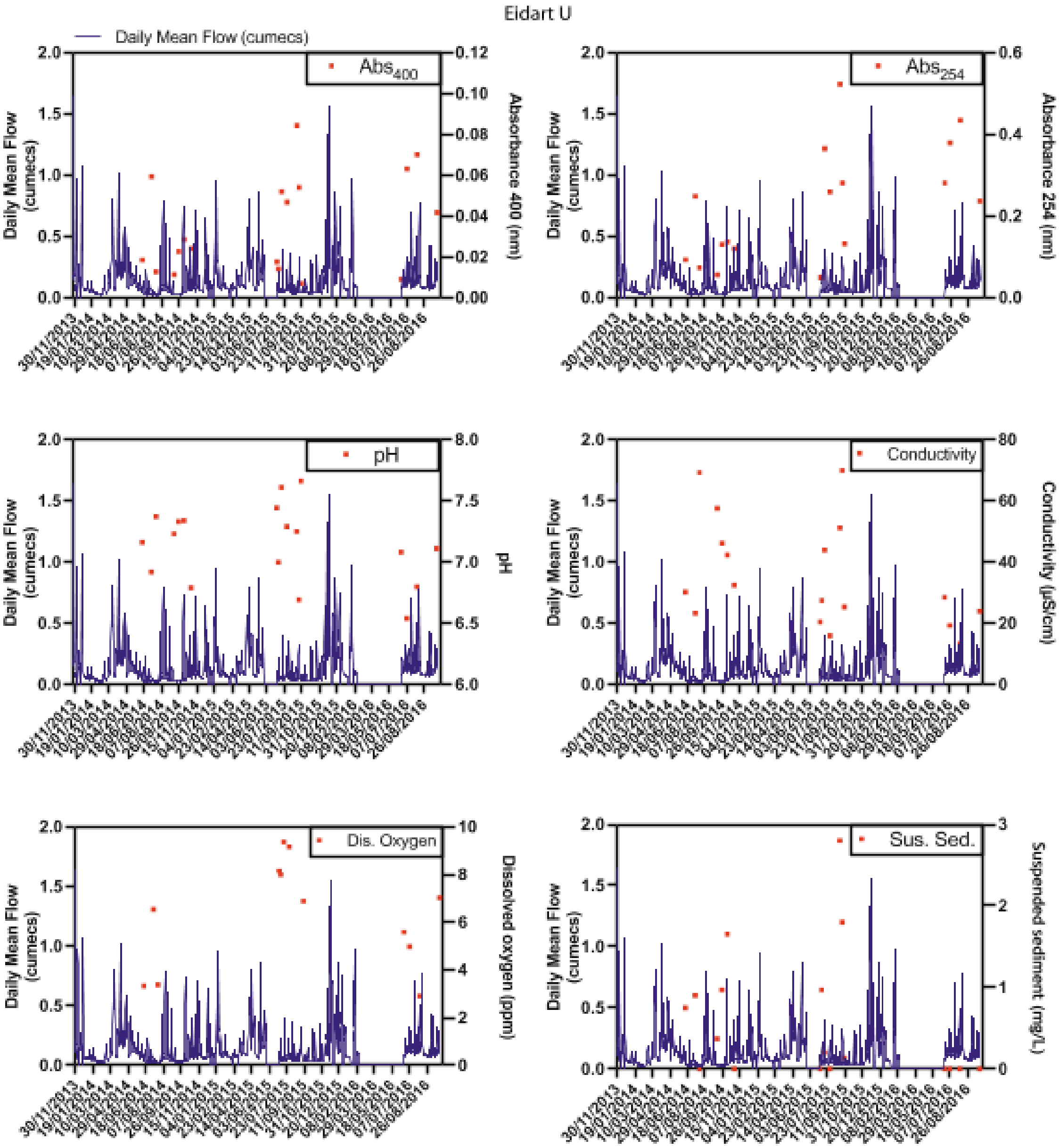

CD NW
Daily Mean Flow (cumecs)
Abs400
Abs254
pH
Conductivity
Dis. Oxygen
Sus. Sed.
Daily Mean Flow (cumecs)
Absorbance 400 (nm)
Absorbance 254 (nm)
pH
Conductivity (µS/cm)
Dissolved oxygen (ppm)
Suspended sediment (mg/L)

C)

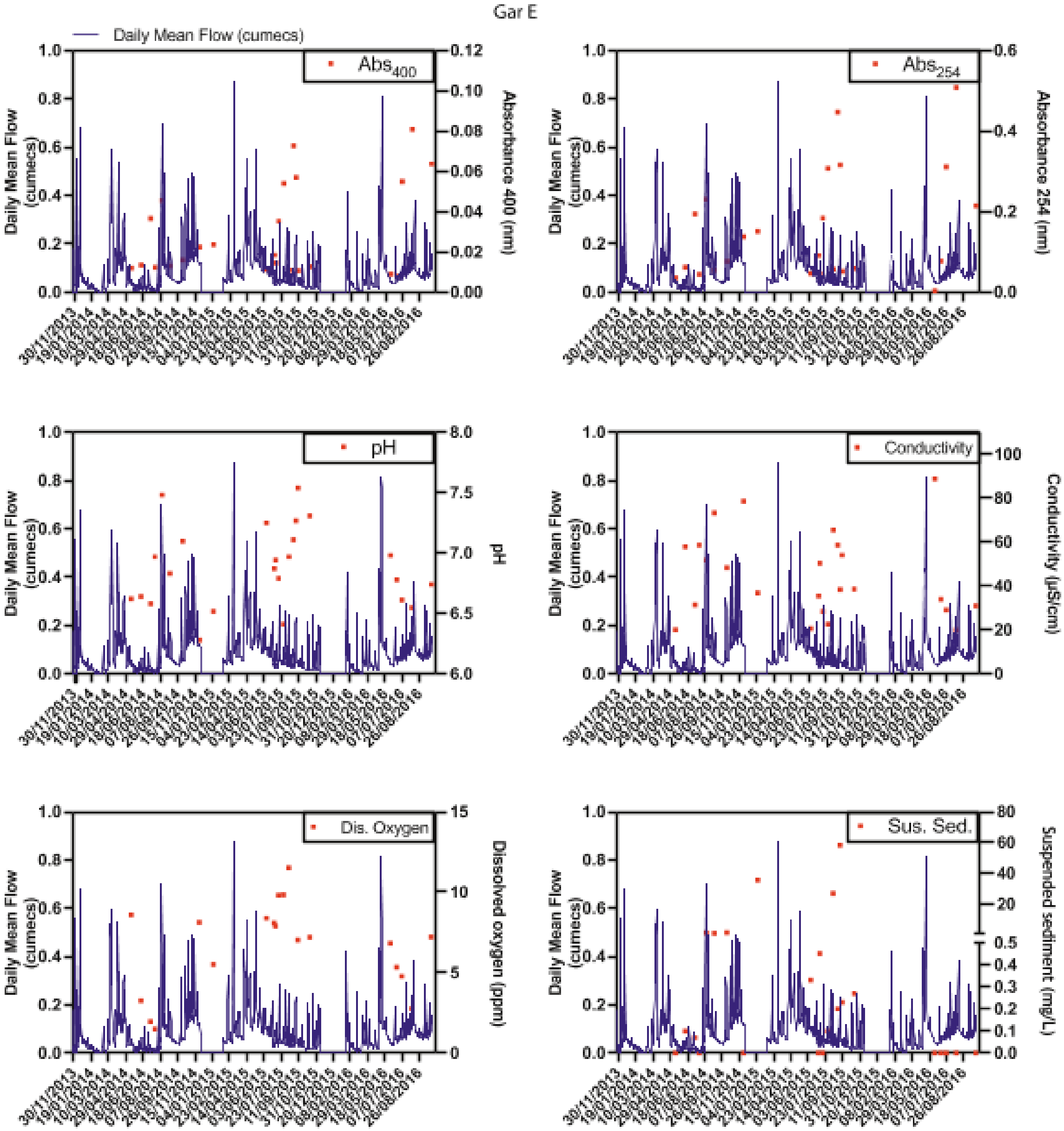


CD U
Daily Mean Flow (cumecs)
Abs400
Absorbance 400 (nm)
Abs254
Absorbance 254 (nm)
pH
Conductivity
Conductivity (µS/cm)
Dis. Oxygen
Dissolved oxygen (ppm)
Sus. Sed.
Suspended sediment (mg/L)
Daily Mean Flow (cumecs)

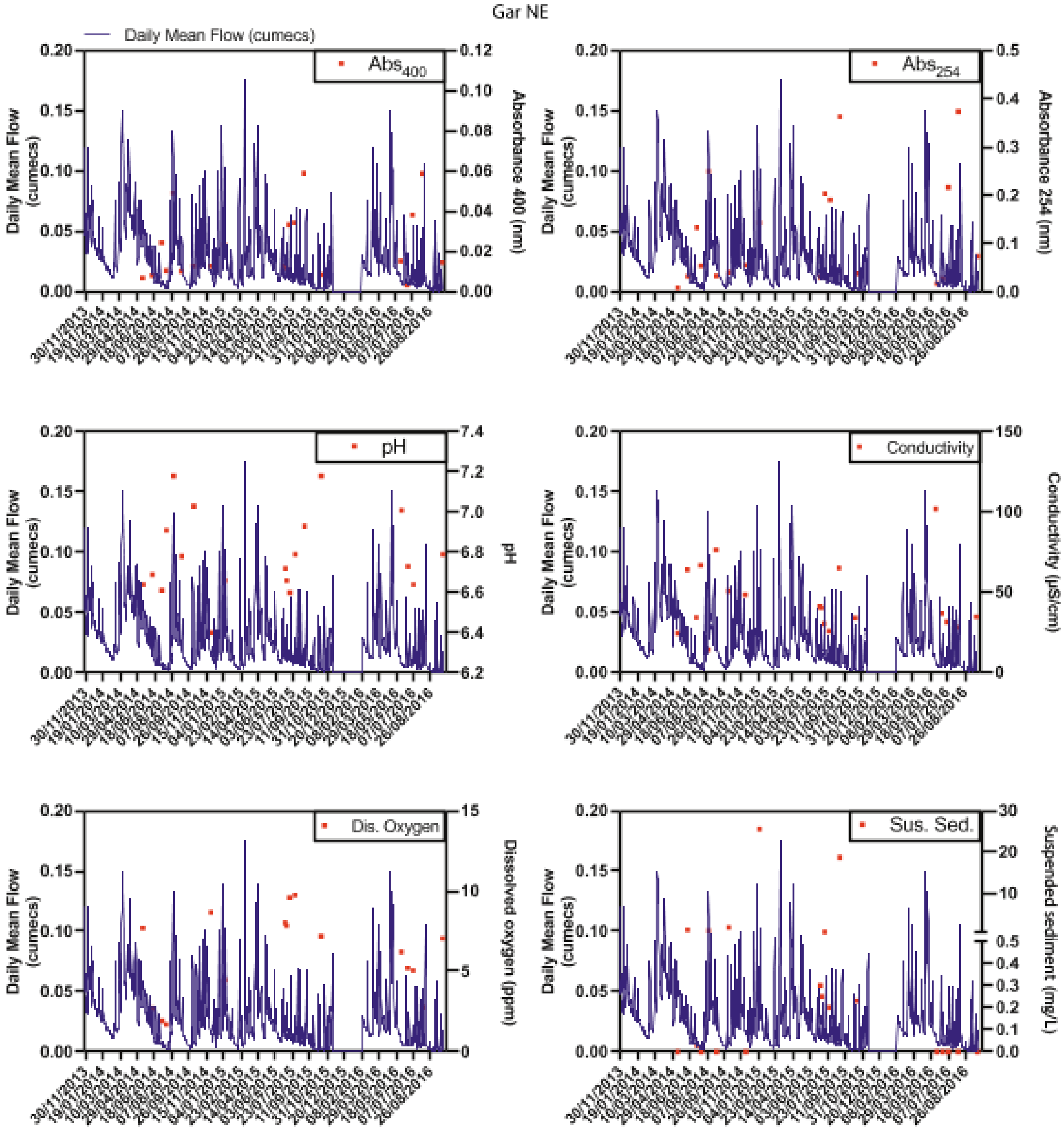
D)


Eidart U
Daily Mean Flow (cumecs)
Daily Mean Flow (cumecs)
Abs400
Absorbance 400 (nm)
Abs254
Absorbance 254 (nm)
pH
Conductivity
Conductivity (µS/cm)
Dis. Oxygen
Dissolved oxygen (ppm)
Sus. Sed.
Suspended sediment (mg/L)

E)


Gar E
Daily Mean Flow (cumecs)
Abs400
Abs254
pH
Conductivity
Dis. Oxygen
Sus. Sed.
Daily Mean Flow (cumecs)
Absorbance 400 (nm)
Absorbance 254 (nm)
pH
Conductivity (µS/cm)
Dissolved oxygen (ppm)
Suspended sediment (mg/L)

F)



Water chemistry and daily flow for; CD L (A) CD NW (B), CD U (C), Eidart U (D), Gar E (E) and Gar NE (F). Within each site, graphs are shown for absorbance at 400nm, absorbance at 254 nm, pH, conductivity, dissolved oxygen and suspended sediment [red marker]. Daily flow [blue line] has been derived for a calendar day.

9.1 Appendix G: DOC export calculation

The DOC flux from each of the streams was calculated using the predicted DOC multiplied by the flow at the sample time. The DOC was then converted to g and divided by the site specific catchment areas in m^2 to give the DOC flux in gC/m^2.

Date	Time (GMT)	Stream	DOC (mg/L)	Flow (L/s⁻¹)	DOC * Flow (mg/s⁻¹)	DOC (g)	DOC Flux (gC/m²)
12/06/2014	11:50	CD L	3.7	98	363	1305	0.28
	12:10	CD NE*	6.1	3	18	66	0.27
	12:20	CD NW	4.5	3	14	49	0.23
	12:28	CD U	4.2	56	235	847	0.37
	11:05	Eidart U	4.4	34	150	539	0.33
	13:56	Gar E	3.7	17	63	226	0.21
	13:32	Gar NE	3.0	15	45	162	0.90
	14:46	MM SE T	3.4	15	51	184	0.16
09/07/2014	10:30	CD L	10.0	89	890	3204	0.70
	11:15	CD NE*	11.9	3	36	129	0.54
	11:45	CD NW	11.0	3	33	119	0.57
	12:00	CD U	10.3	57	587	2114	0.92
	09:15	Eidart U	8.2	39	320	1151	0.72
	13:20	Gar E	6.9	8	55	199	0.18
	13:45	Gar NE	5.4	5	27	97	0.54
	15:00	MM SE T	5.2	12	62	225	0.20
22/07/2014	09:45	CD L	3.1	64	198	714	0.15
	10:10	CD NE*	4.0	3	12	43	0.18
	10:25	CD NW	3.8	3	11	41	0.20
	10:38	CD U	3.5	58	203	731	0.32
	08:45	Eidart U	4.0	36	144	0.5	0.32
	11:15	Gar E	3.3	8	26	0.1	0.09
	11:50	Gar NE	3.5	4	14	0.1	0.28
	12:55	MM SE T	3.5	14	49	0.2	0.15
02/07/2015	13:10	CD L	4.0	119	476	1.7	0.37
	12:20	CD NE*	5.9	3	18	0.1	0.27
	12:05	CD NW	5.1	3	15	0.1	0.26
	13:30	CD U	3.4	35	119	0.4	0.19
	11:05	Eidart U	3.4	40	136	0.5	0.30
	15:00	Gar E	4.4	26	114	0.4	0.37
	14:35	Gar NE	2.9	10	29	0.1	0.58
	15:50	MM SE T	3.5	28	98	0.4	0.31
15/07/2015	10:30	CD L	12.2	147	1793	6.5	1.40
	11:20	CD NE*	15.3	3	46	0.2	0.69
	11:45	CD NW	12.3	3	37	0.1	0.63
	12:10	CD U	10.7	36	385	1.4	0.60
	08:15	Eidart U	11.0	78	858	3.1	1.92
	13:45	Gar E	6.6	27	178	0.6	0.58
	13:10	Gar NE	7.1	12	85	0.3	1.70

	14:40	MM SET	6.0	26	156	0.6	0.49
30/07/2015	13:35	CD L	9.7	152	1474	5.3	1.15
	14:00	CD NE*	9.9	4	40	0.1	0.59
	14:10	CD NW	10.6	4	42	0.2	0.73
	14:25	CD U	10.3	47	484	1.7	0.76
	12:25	Eidart U	8.4	67	563	2.0	1.26
	09:45	Gar E	9.6	56	538	1.9	1.76
	11:05	Gar NE	6.8	12	82	0.3	1.63
	15:05	MM SET	6.9	36	248	0.9	0.78
27/08/2015	11:55	CD L	16.5	383	6320	22.8	4.93
	12:35	CD NE*	17.0	4	68	0.2	1.02
	12:45	CD NW	17.8	4	71	0.3	1.22
	13:00	CD U	17.5	77	1348	4.9	2.11
	08:15	Eidart U	14.8	363	5372	19.3	12.01
	14:15	Gar E	13.0	65	845	3.0	2.77
	13:50	Gar NE	11.0	14	154	0.6	3.08
	15:10	MM SET	15.2	76	1155	4.2	3.65
07/07/2016	10:15	CD L	11.6	51	592	2.1	0.46
	11:40	CD NE*	12.5	2	25	0.1	0.38
	11:45	CD NW	12.5	2	25	0.1	0.43
	11:50	CD U	10.7	77	824	3.0	1.29
	09:15	Eidart U	11.3	116	1311	4.7	2.93
	07:50	Gar E	9.7	70	679	2.4	2.22
	08:30	Gar NE	7.4	8	59	0.2	1.18
	12:50	MM SET	8.5	37	315	1.1	0.99
04/08/2016	10:05	CD L	12.0	133	1596	5.7	1.25
	10:40	CD NE*	16.7	3	50	0.2	0.75
	10:45	CD NW	17.1	3	51	0.2	0.88
	10:55	CD U	16.0	109	1744	6.3	2.73
	09:20	Eidart U	12.7	202	2565	9.2	5.74
	08:40	Gar E	14.5	140	2030	7.3	6.64
	08:15	Gar NE	11.2	14	157	0.6	3.14
	12:15	MM SET	15.9	389	6185	22.3	19.53
30/09/2016	10:45	CD L	8.3	67	556	2.0	0.43
	11:45	CD NE*	10.3	2	21	0.1	0.31
	11:55	CD NW	9.8	2	20	0.1	0.34
	10:15	CD U	8.5	80	680	2.4	1.06
	08:25	Eidart U	7.9	131	1035	3.7	2.31
	14:00	Gar E	7.4	72	533	1.9	1.74
	14:40	Gar NE	4.0	1	4	0.0	0.08
	15:30	MM SET	6.7	24	161	0.6	0.51

* No flow values are available for CD NE but given comparable nature of stream with CD NW, for purpose of completing calculation, flows values for this stream have been used.

To calculate the carbon export values for the monitored years, the DOC values derived from spectro::lyser and flow values from HOBO data logger were used. Measurements were taken over the period 02/06/2014 to 30/09/2016.

Z: = X * (365 / Y)

Where; X is the sum of DOC in gC/m^2/yr. Y is the number of days sampled. Divide to give ratio for one year.

Estimated annual **DOC loss for the MM SE T catchment area (gC/m^2/yr) = Z / 1140000**

Where: Z is the estimated annual DOC loss now converted to grams